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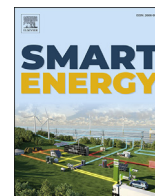
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Energy efficient decarbonisation strategy for the Danish transport sector by 2045

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ABSTRACT

The transport sector contributes to approximately one third of Danish greenhouse gas (GHG) emissions and almost half of emissions from the energy sector. A unified Danish parliament agreed to reduce total emissions with 70% compared to 1990 levels by 2030. This paper estimates the potential for reducing the national transport sector GHG emissions in 2030 and proposes a pathway towards full decarbonisation in 2045 using a complex set of measures.

Towards 2030, the major focus is on an extensive electrification for passenger cars, alongside the implementation of significant measures to achieve lower growth rates for kilometers travelled by car and aircraft. From 2030 onwards, a decisive focus is set on sector integration. Production of electrofuels proves to be a key measure to decarbonize aviation, shipping and long-distance road freight transport.

The results show a reduction of GHG emissions of 41% in 2030 and full decarbonisation in 2045. The reduction is achieved without a significant increase of socio-economic costs. From 2030 to 2045, a substantial electrification of road transport and a focus of moving the need for mobility from roads towards rail and bicycles drives the full-decarbonisation together with the replacement of fossil fuels with electrofuels for aviation, shipping and heavy-duty road transport.

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1. Introduction

The decarbonizing of the transport sector is currently one of the key focuses globally in the effort towards limiting greenhouse gas (GHG) emissions and mitigating irreversible climate change. While a decrease of GHG emissions have been observed in the majority of the energy sector in the European Union, emissions from the transport sector has increased. With the European transport sector, including international shipping and aviation, contributing to approximately one third of total emissions, urgent action is required. Reducing emissions from the transport sector involves a combination of significant reductions in kilometers travelled in energy-intensive modes of transport, a major shift towards shared and zero-emission modes of transport and increases in overall energy efficiencies. Targets to reduce the carbon footprint of the transport sector have been announced in the European Union, but

in order to reach net zero emissions by the middle of this century, drastic measures must be imposed in each country.

In Denmark, the transport sector, including international transport, was responsible for 44 pct. of all CO₂ emissions in 2019 [1]. The burning of fossil fuels in vehicle and vessel combustion engines is the primary driver of emissions. The majority of emissions derives from road transport, which is accountable for 67 pct. while maritime transport and aviation accounts for 31 pct. Over the past decades, a steady increase in travelled kilometers per capita has been observed along with an increase in the stock of passenger vehicles. This development has in relation to the growth in travel demand across all modes of transport, driven an increase in energy demand and hence CO₂ emissions from the transport sector.

Corporation between the Danish Association of Engineers and Aalborg University have since 2006 [2] produced exhaustive energy system strategies towards 100 pct. renewable energy systems in Denmark. In 2006, authors first presented a technical energy system analysis of potentials for renewable energy implementation and efficiency improvement potentials in 2030, along with a vision for a 100 pct. renewable Danish society in 2050. In this work,

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energy efficient measures to limit growth in transport demand and promote modal shifts towards energy efficient modes of transport were presented, and has been further developed since.

The Smart Energy Systems (SES) approach was applied to the energy systems strategy in [3]. Smart Energy Systems are defined as an approach in which smart grids are combined with storage options and organized to integrate synergies between them and thus accomplish optimal efficient solutions for each individual sector and for the overall energy system [4,5]. In [3] a significant part of the transport demand is covered by electricity. Modes of transport that are difficult to electrify, i.e. trucks, aircrafts and sea vessels, face challenges regarding fuel costs and limited bioenergy resources. Here an upscale of electrofuel production is suggested to utilize synergies between electricity, heating and transport sector and decarbonize the transport sector.

This work here builds on the latest report *IDAs Climate Response 2045* [6]. In this work, previous suggestions to reduce growth for inefficient modes of transport in combination with a heavy electrification both via batteries and electrofuels are integrated. IDAs Climate Response 2045 presents a feasible pathway, with a sustainable use of bioenergy, towards a fully decarbonized Danish society in 2045 [7]. In this paper, the proposals and pathway outlined for the transport sector is explored and elaborated.

Literature analyzing renewable energy system transition, show that the transition of the transport sector involves significant uncertainties. The diversity of the sector along with the massive scale globally entails that not one single type of engine or fuel will successfully drive the decarbonisation [8–13]. Instead, a series of measures is needed. It is widely agreed that an extensive electrification of the transport sector is a key measure to reduce energy consumption and GHG emissions from the sector [8,11,12,14]. Electricity stored in on-board batteries can significantly increase the well-to-wheel efficiency of vehicles and will have zero tailpipe emissions. The low energy density of current state-of-the-art battery technologies hinder a full sector-wide transition. With current technology, the on-board batteries presents issues for vehicle weight in order to provide the same range as liquid fossil fuel alternatives. This is an issue for large vessels or aircrafts and for some long-haul heavy duty road vehicles. For these modes of transport, lighter and more energy-dense fuels such as biofuels or synthetically produced fuels from power-to-x pathways (electrofuels) are needed to drive the renewable transition. This presents two main issues, the first one regarding the availability of sustainable biofuels and secondly the prematurity and high costs of electrofuels. Bioenergy is a scarce resource and should preferably not be used where other alternatives are present. The production of electrofuels is currently still only installed at very small scale and for the time being, presents significantly increased costs compared to fossil alternatives. Hence, a reduction of transport demand for energy-intensive modes of transport should be pursued.

In the scientific literature authors have previously evaluated the impacts of the transport sector on the overall energy system.

In [15], authors forecast mobility demand, energy consumption and emissions up to 2050 in the EU. In the TRIMODE model the passenger and freight transport demand is simulated and the amount of vehicles to supply the transport demand is calculated along with the costs. Similarly, in [16] a transport model is applied to a single country to assess and propose a pathway towards a renewable and sustainable transport sector. The model consider only the transport sector, hence no implications on the surrounding energy systems are evaluated.

In [17], authors analyze the effects of modal shifts in a Scandinavian transport system and conclude a possibility to reduce but fuel consumption and emissions from the transport sector in 2050. The authors use a multi-country TIMES model to optimize the

investments in the Nordic transport system by minimizing system costs while satisfying a set of constraints. The modal shifts are enabled via elastic price changes obtained from the shadow price of transportation in the TIMES model. The transport sector is disaggregated into categories of trip lengths to facilitate very specific modal shift measures.

Several studies [18–20] have assessed the efficiency of economic instruments to reduce fuel consumption and/or emissions from the transport sector both for a single country or several.

In this work, measures to reduce and shift transport demand to lower growth and energy consumption are presented and analyzed along with a pathway of implementation of energy efficient, sustainable propulsion technologies and fuels. The bottom-up approach, collecting transport demands based on trip-lengths from all modes of transport, applied in this work allows for analysis in a level of detail that is novel on a national scale. As TransportPLAN is not an optimization model, the pathway created towards 2045 in terms of modal shares, technology implementations and growth rates are up to the user to decide. Furthermore, TransportPLAN allows for a more detailed data input for the hour-by-hour energy system analysis in EnergyPLAN. The focus of this work is the Danish transport sector, but the methodology applied and the derived results provide relevant conclusions for other countries as well.

2. Methodology

The design of a strategy towards decarbonizing the Danish transport sector is modelled using the TransportPLAN and EnergyPLAN tools. In TransportPLAN a bottom-up model of the Danish transport sector is created. Here, it is possible to analyze transport developments in detail and assess the effects of implementations of policy measures or alternative fuels and propulsion technologies. In the hour-by-hour energy system analysis tool EnergyPLAN, system effects of implementations in the transport sector are then analyzed. The combination of the two tools allows for the implementation of very specific transport measurements in TransportPLAN and evaluation of derived systems implications. TransportPLAN is developed as a stand-alone tool, but with the interaction with EnergyPLAN in mind. Combining a detailed bottom-up transport modelling tool with an hour-by-hour energy system analysis tool, allows for very detailed and specific analysis and results.

The combination of a transport model with a full energy system analysis tool enables the evaluation of system effects when proposing scenarios for the transport sector. In this work, the use of EnergyPLAN assists in assessing the investment requirement in renewable energy production capacities to provide efficient energy for the transition towards electro-mobility, the need for installment of electrolysis capacity as well as the need for CO₂ in synthesis processes for the production of electrofuels. The electrification of the transport sector via batteries or electrofuels couples the transport sector and energy system in a new way than what is observed today. In Fig. 1, the general outputs from TransportPLAN and the outputs for EnergyPLAN are highlighted.

2.1. TransportPLAN

TransportPLAN is a back-casting modelling tool, which allows for detailed scenario analysis of transport systems. The detailed resolution of input data provides the possibility of adjusting the development of transport demand precisely and in-depth. The tool requires inputs regarding annual transport demand, vehicle fleet composition, utilization rates and fuel distribution in the first modelling year. Here, data for all modes of transport allocated into

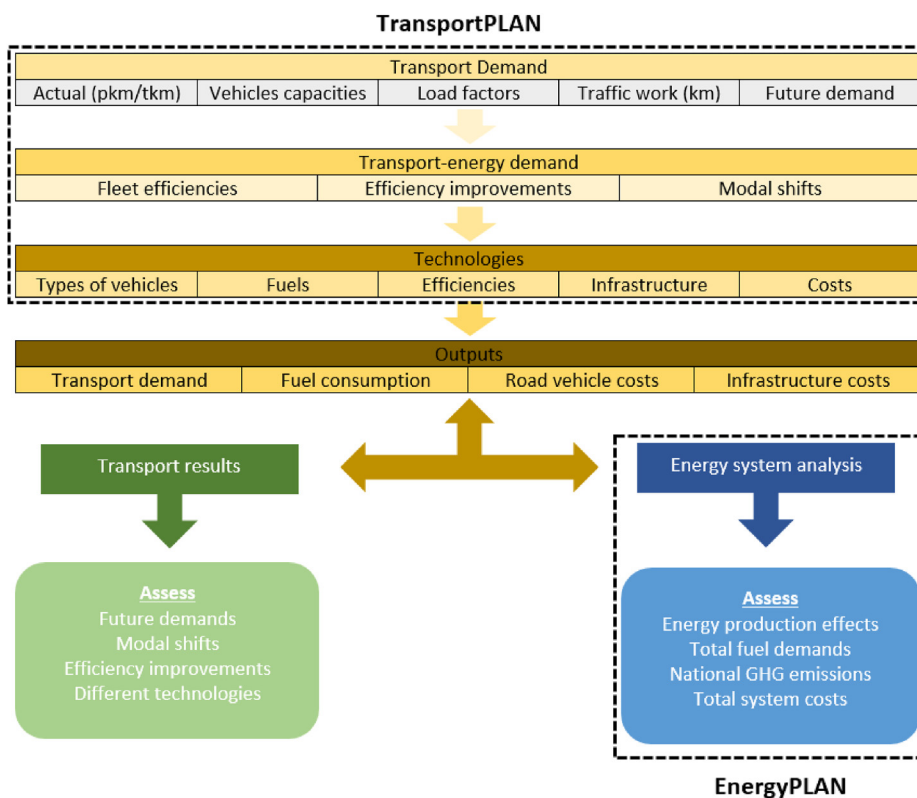


Fig. 1. Methodology applied to analyze the transport sector in TransportPLAN and the outputs from the model that are used in EnergyPLAN.

subcategories of trip lengths were gathered. Transport demand is split between passenger and freight transport, measured in passenger-kilometers for passenger transport and tons-kilometers for freight transport. Transport demand data in combination with capacity utilization factors enables the calculation of total kilometers travelled for all modes of transport (in the following referred to as either traffic work or vehicle-kilometers). Additionally an average energy consumption for the fleet of vehicles for all modes of transport is necessary to calculate the final energy consumption.

The most detailed resolution was obtained for car travel where information regarding trip length and purpose was available. The purpose of travel impacts the utilization capacity of the vehicle, hence the benefits of moving passengers from work related car-trips towards public transport or bicycling are greater than moving passenger from leisure related trips. This is due to the poor capacity utilization of work related car-trips, which in Denmark on average is 1.1 passenger/vehicle [21]. For the remainder of the transport sector data regarding trip lengths and information of national/international trip were gathered.

TransportPLAN is built to enable the development of transport system strategies and scenarios that follow the Avoid-Shift-Improve (A-S-I) approach [22]. The tool provides options to increase/decrease annual growth in transport demand and annual modal shifts across all modes of transport. Additionally the tool allows for creating pathways to implement alternative fuels and propulsion technologies as well as introducing different trajectories for the development of energy efficiency improvements in existing and new engine technologies and improvements in capacity utilization rates. The model results consists of annual transport demand and traffic work for each modelled year, annual final energy consumption, GHG emissions and transport system costs.

These features facilitates an implementation of policy measures or urban development strategies directly into the TransportPLAN

tool and visualize the effects in terms of future traffic work, energy consumption, GHG emissions and transport system costs. The transport system costs includes the costs of road vehicles, fuel production costs and infrastructure costs. Infrastructure costs includes investment and maintenance costs for road and railway infrastructure, charging infrastructure for electric road vehicles and infrastructure costs related to public transport systems and walking and biking infrastructure. All infrastructure costs are calculated based on historic investments and maintenance expenses in relation to historic growth rates. Vehicle costs and costs related to fueling infrastructure for trains, ships and aircrafts are not included in TransportPLAN. The costs of fueling infrastructure for fossil fuels are not included either.

2.2. EnergyPLAN

The modelling of IDAs Climate Response 2045 has been completed using the advanced energy system analysis tool EnergyPLAN [23]. The hour-by-hour energy system analysis tool is designed with emphasis on analyzing the energy system as a whole and coordinate synergies between sectors.

For IDAs Climate Response 2045, EnergyPLAN is used to estimate future needs of biomass resources for the production of electrofuels and the additional renewable energy production capacity needed to supply electricity for electric vehicles and the electricity consumption for CO₂-capture and in electrolysis units. The up-stream energy system effects of measures implemented in the transport sector is important to analyze in a full energy system analysis to understand the implications. With EnergyPLAN it is possible to assess possible energy system synergies in the fuel production for the transport sector, i.e. utilization of excess heat from fuel synthesis in district heating networks or upscaling of hydrogen production from electrolysis units in periods with excess

electricity production from renewables. Thus, using a comprehensive energy system analysis tool such as EnergyPLAN in combination with a transport model provide a more robust foundation for assessment of implementations in the transport sector, that otherwise might be overlooked when using a transport model only.

In EnergyPLAN the transport demand in terms of travelled km is not considered, only the transport-energy demand. Hence, TransportPLAN enables a forecast of transport demand based on travel and transport patterns and developments.

Following the analysis of IDAs Climate Response in TransportPLAN, the scenario is implemented in a fully integrated energy system model of Denmark in EnergyPLAN to analyze and evaluate energy systems effects and synergies. Coupling the transport sector to the power and heat sector via electric vehicles and production of electrofuels improves overall energy system efficiency, but requires an expansion of generation and production capacity.

2.3. TransportPLAN scenarios

This paper aims to design a strategy towards a zero-emission Danish transport sector in 2045 and TransportPLAN enables this. Unlike the general UN methodology, this paper includes energy consumption and GHG emissions of international aviation and shipping.

The development of the Danish transport sector will influence the renewable transition of the entire country significantly. In this work, two future scenarios for the Danish transport sector are outlined and analyzed. The scenarios will represent different trajectories in the development of demand for mobility, transport patterns and propulsion systems. A comparison between a Business-As-Usual (Frozen Policy) scenario and the IDA Climate Response Scenario (IDA2045) is presented in the following. The full IDA2045 scenario represents a decarbonisation strategy for all sectors of the Danish society for 2045. For the transport sector, the IDA2045 scenario will present a pathway towards decarbonisation in 2045, using a combination of measures such as:

- lower growth in traffic work while still accommodating a growing demand for transport and mobility
- comprehensive modal shifts from energy intensive modes of transport towards active modes (i.e. walking or bicycling) and public transport (i.e. buses or railway)
- limiting transport energy demand and GHG emissions by implementing an extensive electrification replacing internal combustion engines with energy efficient electrical engines and substituting energy-dense liquid fossil fuels for aviation and shipping with renewable electrofuels produced by power-to-x pathways

The IDA2045 scenario does not represent the effects of implementing a specific set of measures to achieve a 100% renewable transport sector in 2050. Reaching a 100% renewable scenario can follow many paths, and this work highlights the importance of lower growth and promoting modal shifts to reduce the energy consumption and hence, ease the transition. Transport demands will most likely grow in the future due to infrastructure investments and more affluence among citizens and businesses. However we highlight here, that a slightly smaller growth rate in mobility as well as modal shift may be possible and can have many advantages.

The Frozen Policy scenario is based on the frozen policy scenario published by The Danish Energy Agency in 2019 [24]. The two scenarios will be compared by annual final energy demand, annual transport system costs as well as annual CO₂ emissions.

3. Analysis

3.1. Overview of the Danish transport sector

Figs. 2 and 3 show the details of the composition of the Danish transport sector, for both passenger and freight, in 2020. For passenger transport, the majority of passenger-km (pkm) are covered by car and air traffic, even though >90 pct. of all km travelled are travelled in cars. This is, among others, explained by the poor capacity utilization of cars which on average is only 1.49 passengers/vehicle. The remaining 15 pct. of transport demand and <10 pct. of traffic work comprises traveling by bus, rail, bicycling and walking or by sea.

In freight transport, the majority of goods are transported by sea, hence maritime transport covers >75 pct. of freight transport demand. Trucks and vans cover 24 pct. while rail and aviation only cover approximately 2 pct. of freight transport demand. The capacity of maritime freight vessels compared to road freight vehicles entails that trucks and vans are responsible for the vast majority of total km travelled. The relatively low utilization capacity of truck and vans of approximately 50 pct. on average also contributes to the dominance of traffic work. While the freight transport demand and traffic work covered by aviation and rail are insignificant, they cover 6 pct. of energy consumption. The remaining energy demand is split evenly between trucks, vans and sea transport.

For both passenger and freight transport, a lot of passengers and goods are moved in vehicles with relatively low capacity utilization, thus highlighting the potentials of energy efficiency improvements in the transport sector as a whole. Reducing the traffic work while accommodating the transport demand is a key factor in successfully decarbonising the transport sector. This will also ease the transition from fossil fuels to renewables as less renewable fuels such as electricity, hydrogen and electrofuels are necessary.

Fossil fuels are predominant in the final energy demand in the Danish transport sector (Fig. 4). Almost all road transport consumes diesel or petrol and the small share of renewable biofuels are admixtures. Biofuels cover 4 pct. of fuel consumption, while only 1 pct. is covered by electricity. This is primarily electric trains that receive electricity from overhead wires. In 2020, only 15.500 BEVs and 9.800 PHEVs were registered in Denmark out of 2.650.000 total registered cars [25]. A small share (>1 pct.) of electric and biofuel buses are operational and no trucks or vans are fuelled by renewable alternatives. Jet-fuel for aviation covers approximately 17 pct. of final fuel consumption.

3.2. Increase in demand for mobility

Historically, the growth in transport demand and general demand for mobility have been tightly linked with economic

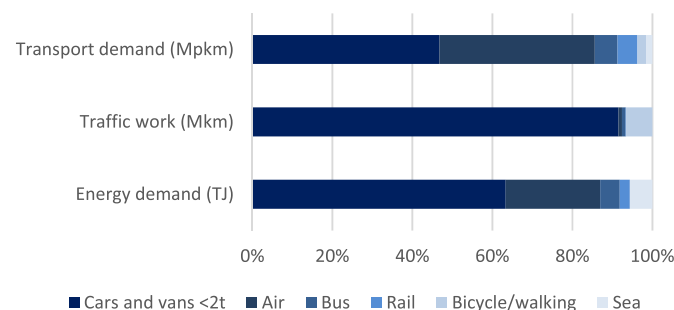


Fig. 2. Transport demand (mpkm), traffic work (mkm) and energy demand (TJ) divided by modes of transport in Danish passenger transport in 2020 [1].

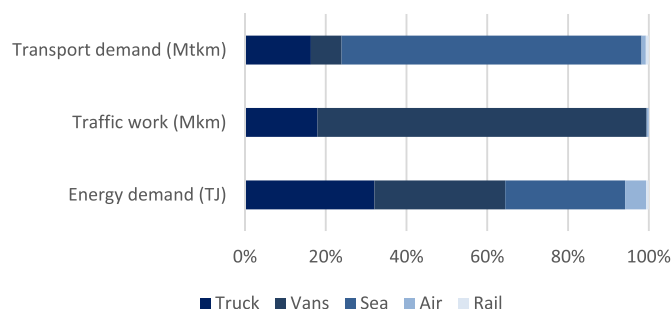


Fig. 3. Transport demand (mtkm), traffic work (mkm) and energy demand (TJ) divided by modes of transport in Danish freight transport in 2020 [1].

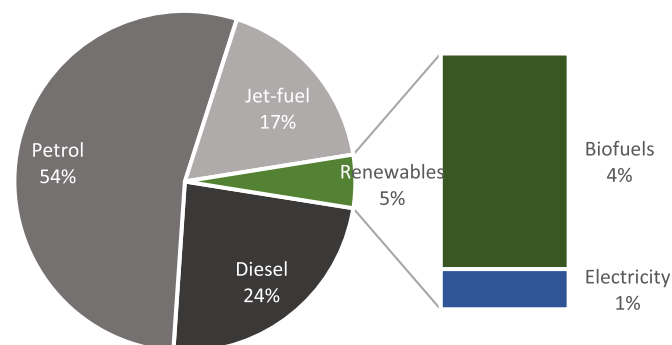


Fig. 4. Share of fuels in the Danish transport sector in 2020 [1].

development. The two have been considered interchangeably correlated, thus economic growth could not be achieved without an increase in mobility while economic growth would prompt an increase in mobility. In reality, the annual vehicle-km travelled (VKT) in cars have, in the developed parts of the world, for the most time followed the development in the gross domestic product (GDP) and gasoline prices. While several researchers [8,26–28] called for a peak-car situation, when annual growth in VKT stalled and in some places decreased in the period between 2004 and 2014 after an ever-growing number of km travelled in cars, this was likely influenced by the global financial crisis and considerable increases in gasoline prices. Growth in annual VKT have since remained stable in several countries in Western Europe, but most of Eastern Europe and the U.S. have experienced an annual growth in VKT/capita since the end of 2014. Since gasoline prices started falling again in 2014, the VKT/capita have been growing in these areas until the COVID-19 pandemic forced a disruption to regularly travel patterns [29–31]. While the authors of this work believe that the amount of cars will reach a level of saturation at one point, there has so far been little or no sign of a decrease in the VKT/capita development in Denmark [32]. For this to happen, a radical change of policies and urban development strategies is needed.

For both the Reference scenario and the IDA2045, the annual transport demand (mpkm) increases from 2020 to 2045 (Fig. 5). In the Reference scenario, this increase is driven primarily by a significant increase in the transport demand for cars. From 2000 to 2018, the annual vehicle-km for Danish cars increased on average 1.6 pct. annually and since 2010, this increase has been 2.5 pct. annually [33]. A contentious increase of 2 pct. annually towards 2045 is assumed in the Reference scenario.

IDA's Climate Response 2045 scenario presents a slight decoupling of growth in mobility and growth in vehicle-km for cars. While the general mobility demand still increases from 2020 to

2045, much of the growth is shifted from cars to other, more energy efficient modes of transport, e.g. railways, buses and bicycles. Additionally the expectations to the annual increase in vehicle-km for cars is reduced. Instead of an annual increase of 2 pct., a 1.6 pct. annual increase is assumed. The shift away from cars towards public transport and bicycles along with a general reduction of annual increase in vehicle-km can be achieved with several measures. A key measure is the implementation of road pricing with varying prices in different zones depending on landing area and usage. A new taxation scheme like this aims to restructure the expenditures of owning vehicles, in a way that the purchase and registration of the vehicle is less cost-intensive and instead the usage and driving in vehicles are taxed more. Road pricing or congestions charges has been discussed in the last decades and several studies found that it could be a more cost-effective measure to reduce car travel and transport sector emissions than extended capacity and expanding public transport infrastructure [34,35]. In [36], authors find that a road pricing scheme in Milan shifted drivers from fossil fuel ICE vehicles towards gas and hybrid vehicles as well as an increase of the usage of motorbikes. This could entail that a stand-alone road pricing scheme will not reduce traffic work, but could encourage the transition towards more sustainable fuels. Instead a road pricing scheme should be introduced in combination with an improvement of public transport systems. A similar study [37], investigating the effects of a congestion charge in Stockholm found that the time-differentiated urban road toll scheme had significant effects on travel patterns. Car traffic in Stockholm was reduced 22 pct. and virtually 50 pct. of the evicted trips were shifted to public transport [35,36,38].

Creating a pathway towards a transport sector supplied by 100 pct. renewable energy requires a present focus on infrastructure investment that enables energy efficient mobility. In IDA's Climate Response 2045, a guiding principle of shifting investments from road infrastructure towards e.g. railways, public transport systems and bicycle infrastructure is followed. This entails that the increase in demand for mobility is not met by an equal increase in car traffic but energy efficient modes of transport such as trains, subways, busses, bicycles etc.

For aviation, IDA's Climate Response 2045 proposes a pathway to reduce transport demand and thus reduce fuel consumption. Airborne travel has allowed for convenient interconnection via long distances that would otherwise not be possible. In order to reduce demand, instruments such as increased fuel and passenger taxes could be utilized. A more expensive ticket price could, in combination with the measures proposed above to enhance public transport and railways, contribute to reduce demand and fuel consumption. The demand for domestic aviation in Denmark is negligible and due to the geographic scale, most routes are less than 300 km. This ensures a potential to shift a lot of these trips towards rail or buses. An improved railway system would provide an attractive alternative, if the journey costs are appropriate. In order to succeed with reducing the impact from aviation, a joint strategy from the EU or a group of European countries is needed.

All of the above measures does not limit the development and accessibility for mobility, but assists in the transition towards a 100 pct. renewable transport sector. The transport demand in IDA's Climate Response 2045 still increases by 45 pct. from 2020 to 2045 but the increase is met by more energy efficient modes of transport. The measures elaborated translates to these specific alterations in the transport modelling tool:

- Attenuation of the growth in pkm for cars from 2 pct. annually to 1.6 pct. in the entire modelling period from 2020 to 2045.
- A shift from cars (2 pct.) and national aviation (10 pct.) towards rail and public transport by 2030. In 2045 additionally 25 pct. of

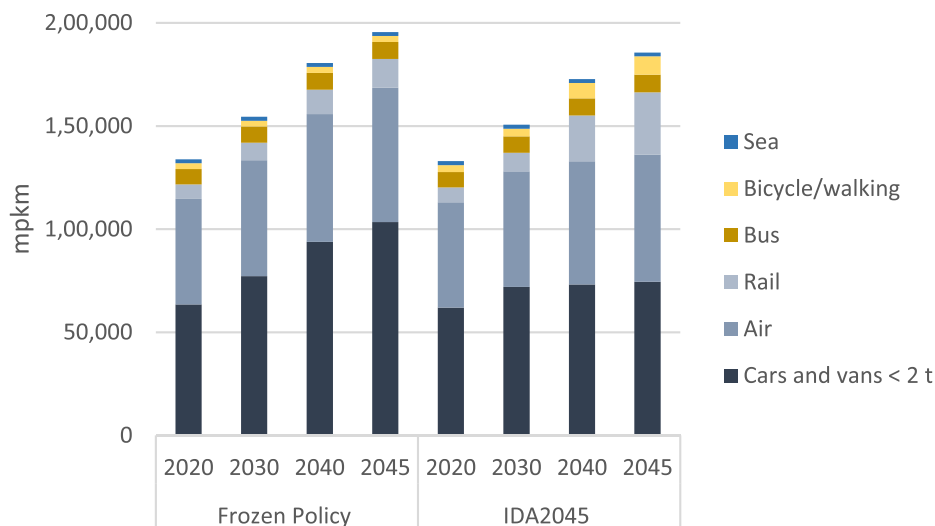


Fig. 5. Development of the annual Danish passenger transport demand from 2020 to 2045 in the Frozen Policy scenario and IDAs Climate Response 2045.

pkm of car transport and 87 pct. of national aviation is shifted towards rail and public transport.

- A shift from cars (2 pct.) towards bicycles in 2030. Additionally 5 pct. from cars towards bicycles in 2045.
- A shift from international aviation (17 pct.) towards international rail in 2045.
- Attenuation of the growth in pkm for national and international aviation by 10 pct. in 2030.

In the IDA2045 scenario, alternate developments for the freight transport demand have not been explored. In *White Paper on Transport* from 2011 [39], the European Commission, formulated targets to shift 30 pct. of freight transport demand from roads towards rail and seaborne transport by 2030 and 50 pct. by 2050. It is uncertain how this will affect the Danish freight transport, which primarily travels for shorter distances. Instead, a single scenario for the development of freight transport demand is investigated in this work. Shipping covers the majority of the international freight transport demand, while road transport is accountable for the bulk of national transport. In Fig. 6, the development of the freight transport demand is outlined. An increase of 10 pct. is assumed,

where the majority comes from growth in national road freight transport.

3.3. Energy efficient transition

In order to successfully implement a transition towards a fully decarbonized transport sector in 2045, IDA's Climate Response 2045 proposes a combination of alternative propulsion technologies along with a pathway for renewable production of electrofuels to substitute energy-dense fuels for primarily aviation and maritime transport. A reduction in the growth in VKT for cars decreases the annual fuel consumption substantially, but an implementation of energy efficiency improvements and replacing fossil fuels with renewable alternatives will still be necessary.

3.3.1. A strategy of heavy electrification

In 2045, IDA's Climate Response suggests that all internal combustion engine (ICE) cars and vans are replaced with battery electric vehicles (BEV). The substantial developments in battery technologies in recent years has allowed for a realistic implementation of large shares of BEVs [40–42]. Along with technology

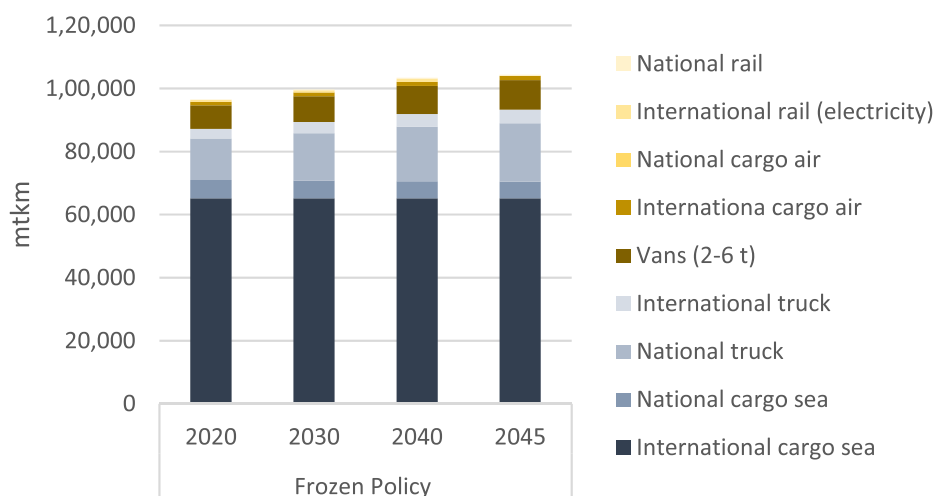


Fig. 6. Development of the annual Danish freight transport demand from 2020 to 2045 in the Frozen Policy scenario.

developments, several European Union member countries have proclaimed a ban of ICE vehicle sales between 2030 and 2040 [43–45]. The well-to-wheel (WtW) efficiencies of BEVs compared to ICE vehicles are approximately three times higher. Hence, replacing all ICE cars and vans with BEVs significantly reduces total energy consumption. The purchase price of BEVs are currently higher than ICE vehicles, but there is a widespread agreement that decline in battery production costs and efficiency improvements of assembly and production will ensure price competitiveness between the two already during the middle of this decade [46–49]. For trucks, the same pattern is observed although the time of price parity may arrive later for the heaviest vehicles [50,51]. The implementation of electricity in IDAs Climate Response reduces the consumption of gasoline and diesel from 102 PJ in 2020 to 59 PJ in 2030 for Danish passenger transport. To accommodate the transport demand in 2030, approximately 1.3 million BEVs and plug-in hybrid electric vehicles (PHEV) are needed (Fig. 7). The PHEVs are not suggested as a long-term solution towards 2045, but they are expected to play a role towards 2030.

The strategy of electrification is also followed for Danish railways and buses. An extensive electrification of the railway system is already being rolled out with a combination of overhead wires and battery electric trains. For buses, it is estimated in IDA's Climate Response 2045 that it is possible to replace 75 pct. of the transport demand with battery electric buses. This cover all the urban buses and 50 pct. of the regional and inter-city buses. A less significant shift towards BEVs is suggested for heavy-duty road transport. It is estimated that all trips less than <150 km can be directly replaced by battery electric trucks (BET). The rapid development of battery technology also affects the development of BET, but there are still uncertainties and disagreements between researchers and the vehicle manufacturers of whether BETs will be able to support heavy loads and long distances [52–55]. In order to assist the electrification, IDA's Climate Response 2045 proposes an implementation of Electric Road Systems (ERS) to allow for in-motion charging. This technology is still only at demonstration state for road transport, but has been used and developed for decades for railway transport. ERS represents a large infrastructure investment, but could offer an energy efficient solution to electrify heavy-duty road transport [56–58].

The additional investment costs for electric vehicles in IDA's Climate Response compared to the Frozen Policy scenario from 2020 to 2030 are 9.8 billion Euro. These covers the investment in 1.3

million PHEV and BEV cars, the electrification of buses and trucks including minor investments in pilot projects for ERS. From 2030 to 2045, the corresponding costs are 7 billion Euro. The costs covers an approximately 5.6 billion Euro to replace the remaining ICE passenger cars with BEVs, 0.5 billion Euro to substitute ICE buses and trucks with BEVs and 1 billion Euro in investment costs for approximately 400 km of ERS. The total investment costs are lower in the period from 2030 to 2045, primarily due to an expectation of decreased purchase prices for BEVs concurrent with the development of battery technology. For transport system infrastructure investment are required for expansion of railway network and improved charging infrastructure for BEVs. The historic costs of increased transport demand on rail in Denmark have been close to identical to the costs of increased transport demand on road [32]. Hence, the proposed modal shift from road to rail in IDA's Climate Response entails no additional infrastructure costs. The costs of expanding a reliant network of charging stations for BEVs amounts to 0.4 billion Euro in 2030 and additionally 0.7 billion Euro from 2030 to 2045.

For aviation and shipping, electrification is currently only applicable for few specific usages. In IDA's Climate Response 2045, all domestic ferries are electrified in 2045. The trip length of Danish ferries, except the route to the island Bornholm, are short and it will be possible to equip a battery and charging stations at each port. For aviation, battery electrification is proposed only to have an insignificant role. The energy density of Lithium-ion batteries currently represent the primary limitation to electric aviation. Projections of state-of-the-art battery energy density is estimated [59] to reach 500 Wh/kg in 2025 and possible higher in the following years. This however is still far from the average energy density of liquid jet fuel of approximately 11,900 Wh/kg [42]. Instead electric engines with hydrogen fuel cell propulsion systems are assumed to have an influence on short-haul flights [42,60]. Several roadmaps, investigating the decarbonisation of aviation [61–63], suggest a production of sustainable aviation fuels, i.e. advanced bio jet fuels and electrofuels produced from power-to-x pathways.

To accommodate the remaining transport demand, that is not fit for electrification, IDA's Climate Response proposes a significant upscale of electrofuel production. Electrofuels produced from renewable electrolytic hydrogen combined with a source of carbon or nitrogen in fuel synthesis, allows for a sustainable, energy-dense hydrocarbons or ammonia, that can directly replace fossil fuels like jet-fuel, heavy fuel oil (HFO) for shipping etc. Electrofuels fills the

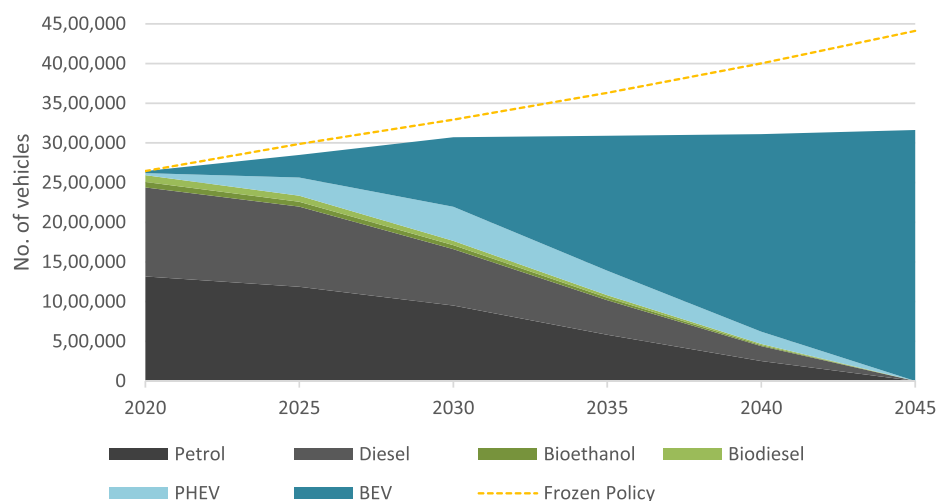


Fig. 7. No. of cars in IDA's Climate Response 2045 divided by fuel consumption. Yellow line is the no. of cars in the Frozen Policy scenario.

direct purpose of replacing fossil fuels in sectors that are otherwise hard to decarbonize, while providing a flexibility service to integrate large penetrations of renewable energy into the energy system.

For heavy-duty road transport, IDAs Climate Response proposes that 55 pct. of the fossil fuel consumption is replaced with electrofuels and 10 pct. with hydrogen in 2045. Hydrogen is expected to be utilized in niche markets and only take up a relatively small market share. Building a hydrogen infrastructure to support a full transition is not believed to be feasible, instead electrofuels like methanol or DME are proposed to replace diesel.

For the majority of maritime transport, where battery electrification is unfeasible a combination of ammonia and methanol is proposed. Hydrogen from electrolysis is combined with nitrogen in fuel synthesis to produce ammonia that should replace 50 pct. of fossil fuels in the maritime freight transport, while the remaining fossil fuels are replaced with methanol. For aviation, IDAs Climate Response suggest that electric aircrafts should cover 25 pct. of the shorter inter-European routes of less than 1000 km and hydrogen powered aircrafts should cover 10 pct. of the longer routes of more than 1000 km. The integration of electric and hydrogen aircrafts on these routes will cover approximately 14 pct. of the aviation transport demand in 2045, after the implementations of measures to reduce the transport demand by air. The remaining transport demand is proposed to be covered by e-kerosene produced from power-to-X pathways (see Fig. 8). In Fig. 9, the annual fuel consumption and CO₂ emissions for the Frozen Policy scenario and IDAs Climate Response are compared.

3.4. Transport system costs

Total transport system costs in IDA's Climate Response are reduced 4.4 pct. in 2030 compared to the Frozen Policy scenario (Fig. 8). The lower growth in transport demand for cars is the main reason for the reduction. The lower growth results in fewer cars which counterbalances the higher purchase price of BEVs compared to ICE vehicles. The lower growth significantly reduces annual road infrastructure investment and maintenance costs, and the energy efficient BEVs also reduce annual fuel costs. Additional costs for railway infrastructure, charging infrastructure and bicycling and public transport infrastructure are needed in IDA's Climate Response (see Fig. 10).

In 2045, IDA's Climate Response reduces annual transport system costs compared to the Frozen Policy scenario by 10 pct. The lower growth in transport demand for cars along with notable

modal shifts towards public transport and bicycling are still significantly important. The investment in vehicles are reduced 20 pct. compared to the Frozen Policy scenario. The anticipated reduction in the costs of BEVs ensures that the full economic effects of reducing growth and enforcing modal shifts are achieved. Investment and maintenance in road infrastructure are reduced by half compared to Frozen Policy, while investments in rail are doubled and hence counterbalances any potential savings. Fuel costs increase in 2045 in IDAs Climate Response as production of electrofuels are scaled up to decarbonize the heavy-duty road transport, aviation and shipping sector. The development of production costs of electrofuel is expected to be 3–4 times higher than fossil alternatives in 2045 [64]. Hence, the fuel savings from replacing fossil fuels with electricity in most of passenger road transport is cancelled out by the electrofuel production costs. As in 2030, additional costs for charging, bicycling and public transport infrastructure are necessary in 2045 in IDAs Climate Response.

3.5. Biomass, renewable energy capacity and transport

The proposed transport measures in IDAs Climate Response calls for a significant upscale of several technologies, some of which are currently only operating at small scale or in demonstration facilities. Most important is the extensive integration of renewable electricity production capacity, i.e. in the form of wind turbines or solar photovoltaics. This is required to provide power for electric vehicles, ferries, aircrafts and electrified railways along with electricity consumption in electrolysis plants and carbon capture installations. In 2030, an electrolysis capacity of 1200 MW is needed to produce approximately 12.2 PJ of electrofuels for heavy-duty transport, aviation and maritime transport. Hydrogen and electrofuels consumption increases to 84 PJ in 2045, which requires additionally 3600 MW of electrolysis capacity.

In order to supply the electricity consumption in IDAs Climate Response a capacity of 2700 MW offshore wind needs to be installed by 2030 and 9750 MW in 2045. The electricity consumption in vehicles, aircrafts, vessels and trains increases from 2.3 PJ in 2020 to 19 PJ in 2030 and 28.6 PJ in 2045. Additionally, the electricity demand for electrolysis and carbon capture increases significantly in the same period.

CO₂ from both point capture and biomass is utilized in the production of electrofuels. In 2030, 200 MW gasification of wood-chips is installed and in 2045, 2000 MW capacity divided between gasification, pyrolysis and hydrothermal liquefaction (HTL) is installed.

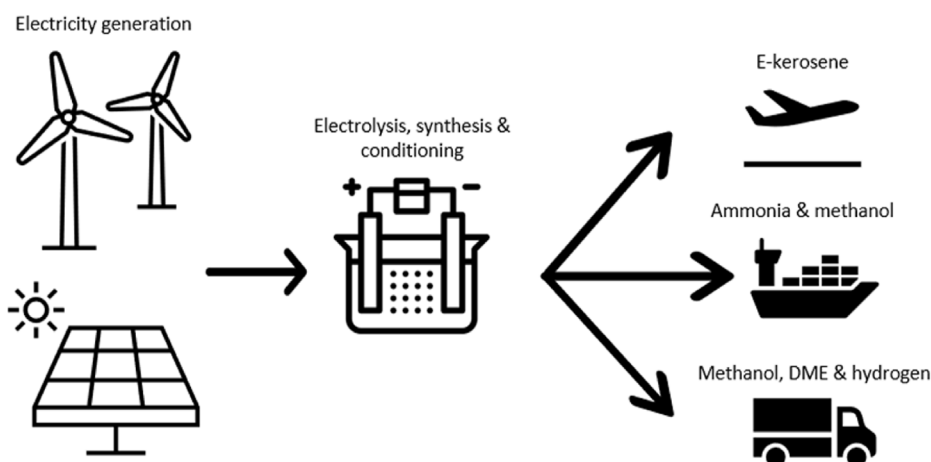


Fig. 8. Simplified electrofuel production pathway. The hydrogen from electrolysis is combined with carbon or nitrogen to produce ammonia, methanol, DME or E-kerosene.

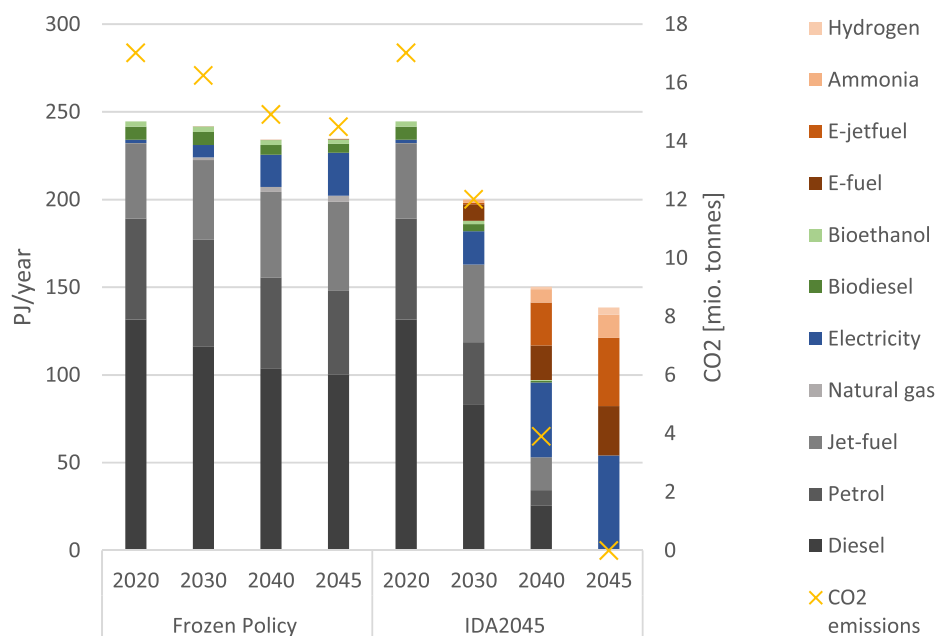


Fig. 9. The fuel consumption in the Danish transport system in the Frozen Policy scenario and IDAs Climate Response 2045. Annual CO₂ emissions indicated by the yellow x on the secondary y-axis.

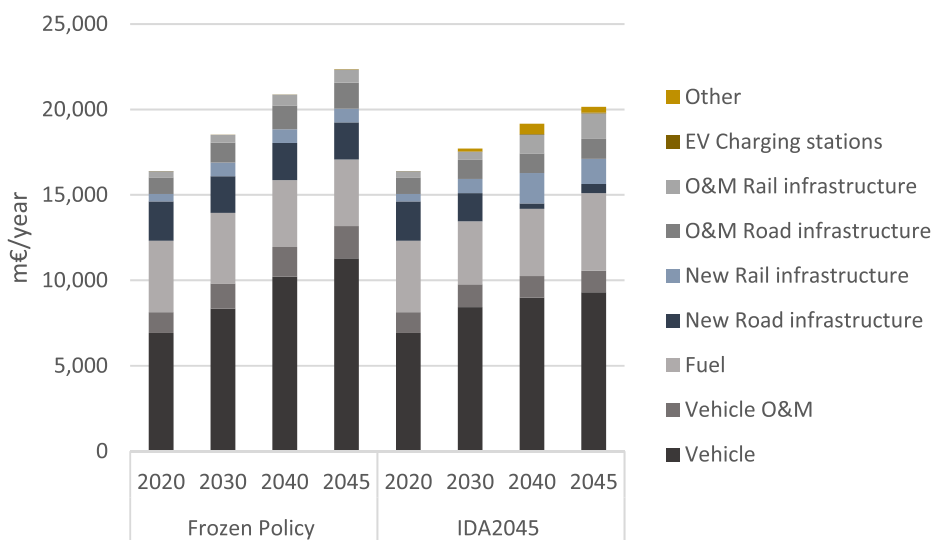


Fig. 10. The annual transport system costs in the Frozen Policy scenario and IDAs Climate Response 2045.

4. Conclusion

In this paper, a comprehensive transport modelling tool has been presented and applied to the case of decarbonizing the Danish transport sector by 2045. The modelling tool TransportPLAN is a bottom-up back-casting transport model that allows for the user to assess the implementation of measures to lower the growth of transport demand, promote modal shifts and introduce novel and alternative propulsion technologies and fuels.

Designing a pathway for decarbonizing the Danish transport sector is complex, especially when accounting for the Danish share of international aviation and maritime transport. This significantly increases the demand for bioenergy and the production of electrofuels, which inflate transition costs and presents the issue of sustainable use of bioenergy resources.

IDAs Climate Response presents a pathway that is technically doable to fully decarbonize the Danish transport sector by 2045. In order to reach this scenario, a series of measures are necessary to implement. The main focus should be on lowering the growth of transport demand in inefficient modes of transport while not compromising the development and growth of mobility. In IDAs Climate Response several measures are implemented to reduce growth in car travel and create modal shifts towards public transport and active modes of transport as bicycles and walking. A way of achieving this, proposed here is with political instruments, i.e. the introduction of a road price scheme and urban planning measures such as building extensive infrastructure for both rail and public transport system and bicycle pathways. Lowering the growth of transport demand for aviation is proposed, achieved with the introduction of elevated passenger-taxations to increase the

ticket purchase price and improvement of railway infrastructure to enhance transport alternatives.

Lowering the growth of transport demand in energy-intensive modes of transport ease the transition towards a full decarbonisation, both in terms of energy production and total costs. In order to reduce GHG emissions, IDAs Climate Response proposes a pathway of heavy electrification. Almost all fossil fuels in road vehicles are replaced with batteries except for a quarter of the transport demand for busses and for trips longer than 150 km for trucks. All railways are electrified, while national ferries and some short-distance aviation are also converted to electric propulsion. The remaining transport demand is met with hydrogen or electrofuels. The fully decarbonized transport system in 2045, presented in IDAs Climate Response reduces total transport system costs compared to a Frozen Policy scenario by 10 pct.

Declaration of competing interests

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests. The research presented in this paper is based a collaboration with Aalborg University and the Danish Society of Engineers (IDA). This research was funded by the Innovation Fund Denmark, grant number 6154-00022B RE-INVEST – Renewable Energy Investment Strategies – A two-dimensional interconnectivity approach project.

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