Transportation in the GreenREFORM model

An introductory note

Preliminary, do not cite.

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Abstract

This note provides an introduction to and overview of the transportation sector in the GreenREFORM model and highlights important observations for the design of the model. The note initially describes the structure of the transportation sector in the Danish National Account statistics including households' own transportation, and the associated stock of vehicles and fuel consumption. The impact on the environment from transportation is also presented and the role of the transportation sector in the green transitioning of the Danish society is discussed. In this context, the importance of upstream processes such as the production of fuels and refueling infrastructure for fuels is highlighted. Finally, the note gives an intuitive introduction to the transport module in the GreenREFORM model by dicussing the main components of the model.

Keywords: Transportation and the Environment, Green Transition, Technological Adoption, Alternative Fuels.

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1 Introduction

The primary objective of the model for transportation in GreenREFORM is to describe the green transition of the Danish transportation sector and the associated marginal cost of abating greenhouse gas (GHG) emissions. The model focuses on describing the role of technological substitution (e.g. improving fuel efficiency and switching to low-carbon fuels) and modal shifts in transitioning the transportation sector and abstracts from other pathways for decarbonizing transportation such as autonomous vehicles and vehicle sharing. In doing so, special emphasis is put on (i) describing the supply of and demand for transportation services along with the use of different vehicle technologies and their related fuel consumption and emissions and (ii) explicitly accounting for upstream processes related to the supply of fuels consumed by vehicles.

The description of transportation services in the transportation model is based on detailed (Green) National Account statistics made available by Statistics Denmark. Relying on this novel data set, the transportation model accounts for the primary modes of private and public transportation within road-, rail-, sea-, and air transportation. The purpose of this dis-aggregation of transportation services in the statistics is to appropriately capture the heterogeneity of transportation services and allow for more thorough analyses of the substitution possibilities between transportation modes as well as the role of modal shifts in decarbonizing transportation. Furthermore, recognizing that future prospects for low emission transportation services are to a large extend determined by the vehicle fleet, the model also incorporates a heterogeneous stock of vehicles by using a dis-aggregated inventory of the current vehicle fleet. The vehicle fleet data is also made available by Statistics Denmark for the GreenREFORM model. Compared to the homogeneous capital stock of transport equipment available in the standard National Accounts statistics, GreenREOFRM's stock of transportation capital is heterogeneous in both vintages and prime mover (prime mover is referred to as vehicle technologies in this note). Importantly, this level of vehicle heterogeneity allows for technological change in two dimensions: First, technological change in the transportation sector is embodied in new vintages from the improvements in existing technologies, where embodied technological change is primarily energy saving. Second, new vehicle technologies become available in the future and diffuse if they are cost-efficient. In this context, the data describing future improvements in existing vehicle technologies as well as the development of new ones is based on the Danish Energy Agency's (2016) well-to-wheel analysis of alternative fuels in the transportation sector, which also has an accompanying data set (henceforth *bottom-up data*).[1] The bottom-up data is a forecast of technological and economic variables associated with different vehicle technologies (consistent with Statistics Denmark's fleet data) until 2050 based on historical trends and expert opinions. Given that Denmark is a small open economy and the GreenREFORM model is an exogenous growth model, the bottom-up data is taken as exogenous input in the model.

The adoption of new vintages and vehicle technologies is endogenous and given by a discrete-continuous investment model. In order to account for the observed rigidity of the vehicle fleet, vehicle

[1]The data can be retrieved at `https://ens.dk/sites/ens.dk/files/Analyser/alternativ_drivmiddelmodel_3.0_2.xlsm`.

investment is subject to transaction costs, giving rise to a discrete choice, i.e. whether to invest or not. The continuous choice is how much to invest subject to quadratic adjustment costs. The presence of transaction and adjustment costs implies that the model exhibits considerable adjustment lags in the vehicle fleet, which may explain the observed rigidity in the historical data. [åben dør?] Note, that there are no adjustment lags in the stock of vehicles from the supply side. The adjustment costs comes exclusively from the demand side.

The model also includes upstream processes related to fuels' value chain. Upstream processes are relevant for determining the technological possibilities and the marginal costs of abating emissions from the transportation sector for two primary reasons: First, the marginal abatement cost of replacing e.g. internal combustion engine cars with electric ones depends on how power is produced in the electricity sector and how increased power demand for transportation purposes affects the electricity system. Second, heavy land-, sea-, and air transportation are expected to rely on conventional vehicle technologies in the foreseeable future and these areas of the transportation sector are therefore more likely to rely on green counterparts (e.g. bio-fuels) of fossil-based fuels. The primary place of technological substitution may therefore take place in the production of alternative fuels.

By endogenizing the supply chain of fuels - from the extraction of primary energy and production of feedstocks to the distribution of fuels via a network of refueling stations - the model accounts for both the economic costs and external effects of supplying fuels. In this context, the model also relies on the bottom-up data because it contains similar information for representative fuel producing technologies and fuel distribution networks. Among these are so-called power-to-X (PtX) technologies. The Danish transmission system operator, Energinet, and Energi Danmark[2] highlighted in a recent report (see Energinet & Dansk Energi, 2020) that PtX must play a part if Denmark is to reduce emissions from the share of energy consumption that cannot be electrified such a heavy land-, water-, and air transportation. While there is still work to be done in relation to describing the transportation and storing of hydrogen as well as the carbon capture needed to use PtX (CCU), the transportation model also includes PtX technologies used to supply fuels for the transportation sector.

Finally, it is important to highlight that external effects in fuel supply chains are not limited to climate- and environmental-related effects, because the fuel distribution network exhibits indirect network effects that potentially influence the speed of adoption of alternative vehicle technologies.

Positive indirect network effects arise because more users in a given network of refueling stations increases the incentive to develop a more dense network, which, in turn increases the value of the vehicle itself. In other words, the complementarity of vehicles and fuel distribution networks create complementarity in consumers' vehicle purchases. A range of empirical work has documented indirect network effects for electrical vehicles (see Zhang et al., 2016; S. Li et al., 2017; J. Li, 2019; Springel, 2019) but it is generally recognized that such network effects also exist for other alternative fuels.[3] The

[2]Energi Danmark is a major player in wholesale electricity trade in Denmark and one of the leading energy trading groups in the Nordic regions.

[3]The EU has adopted the Alternative Fuels Infrastructure Directive, which requires member states - amongst others - to develop a national policy framework for the development of alternative fuels and their infrastructure.

normative policy implications of such network effects are important if they are externalities, i.e. if a consumer does not internalize that her purchase of a vehicle increases the incentives of other consumers to adopt the vehicle technology as well. It relates the point raised by Acemoglu et al. (2012), that subsidies may be necessary to avoid the excessive use of carbon taxes due to positive externalities affecting the diffusion of green technologies. This point has also been reiterated by Greaker & Midttømme (2016) in the context of vehicle adoption: They determine the optimal diffusion of clean vehicles in a theoretical model and find that a failure to account for network effects in emission taxes lead to excess inertia, i.e. a sub-optimally low diffusion of clean vehicles. The transportation model in GreenREFORM includes such network effects, however, important aspects such as the locational choice of refueling stations and compatibility issues are abstracted from.

The rest of the note is organized as follow: Section 2 describes the structure of the transportation sector in the Danish National Accounts including the stock of vehicles and fuel consumption. Section 3 discusses the transportation's impact on the environment as well as other important external effects from transportation. Section 4 elaborated on upstream process related to the supply of fuels and the relevance for transition the transportation sector. Finally, section 5 gives an intuitive introduction to the transport module in the GreenREFORM model by presenting the main components of the model.

2 Structure of the transportation sector in the National Accounts

Before diving right into the National Account statistics for the transportation sector some terminology clarifies the overall structure of the sector.

Terminology. It is convention to distinguish between the transportation sector and the transportation industry. While the transportation industry is the sum of all industries characterized as an *for hire* transportation industry in the National Accounts, the transportation sector encompasses transportation services from all economic activity. That includes *for own* transportation services from non-transportation industries and households' own transportation. The transportation sector is therefore a more inclusive term than transportation industry. This distinction is relevant, because the supply of (especially road) transportation services occur - to a smaller or larger degree - in all parts of the economy. That is, in many cases a single industry supplying a certain road transportation service cannot be isolated in the National Accounts. Hence, all non-transportation industries produce transportation services as part of the product they are selling, commonly referred to as for own transportation.

The for hire transportation industries are listed in table 4 according to two levels of industry groupings in the National Accounts, the 69-grouping and the 117-grouping, as well as the industry definitions in the national version of EU's nomenclature, the Danish Industrial Classification of All Economic Activities 2007, commonly referred to as *DB07*. DB07 is the most dis-aggregate list of national industries.

Transportation activity. The for hire transportation industry has increased its gross value added (GVA) by 20% between 2010-2018, amounting to 2.3% increase per year.[4] However, the industry accounts for

[4] Statistics Denmark, table NABP36.

Table 1: The transportation industries according to the Danish National Accounts

69-grouping[1]		**117-grouping[1]**		**DB07[1]**	
nr.	label	nr.	label	nr.	label
49.00.00	Land transport, pipelines	49.00.1	Interurban rail transport	49.10.00	Interurban passenger rail transport
49.00.00	Land transport, pipelines	49.00.1	Interurban rail transport	49.20.00	Interurban freight rail transport
49.00.00	Land transport, pipelines	49.00.2	Suburban trains, buses & taxi operation.	49.31.10	Urban & suburban buses
49.00.00	Land transport, pipelines	49.00.2	Suburban trains, buses & taxi operation.	49.31.20	S-trains and metro
49.00.00	Land transport, pipelines	49.00.2	Suburban trains, buses & taxi operation.	49.32.00	Taxi
49.00.00	Land transport, pipelines	49.00.2	Suburban trains, buses & taxi operation.	49.39.10	Interurban buses and school buses
49.00.00	Land transport, pipelines	49.00.2	Suburban trains, buses & taxi operation.	49.39.20	Coaches and other land passenger transport
49.00.00	Land transport, pipelines	49.00.3	Road freight transport, pipeline	49.41.00	Freight road transport
49.00.00	Land transport, pipelines	49.00.3	Road freight transport, pipeline	49.42.00	Moving companies
49.00.00	Land transport, pipelines	49.00.3	Road freight transport, pipeline	49.50.00	Pipelines
50.00.00	Water transport	50.00.0	Water transport	50.10.00	Sea and coastal passenger transport
50.00.00	Water transport	50.00.0	Water transport	50.20.00	Sea and coastal freight transport
50.00.00	Water transport	50.00.0	Water transport	50.30.00	Passenger transport by inland waterways
50.00.00	Water transport	50.00.0	Water transport	50.40.00	Freight transport by inland waterways
51.00.00	Air transport	51.00.0	Air transport	51.10.10	Scheduled passenger flights
51.00.00	Air transport	51.00.0	Air transport	51.10.20	Charter & and taxi flights
51.00.00	Air transport	51.00.0	Air transport	51.21.00	Air freight transport
51.00.00	Air transport	51.00.0	Air transport	51.22.00	Aerospace
52.00.00	Support activities for transportation	52.00.0	Support activities for transportation		*
53.00.00	Post and courier activities	53.00.0	Post and courier activities		*

Source: Statistics Denmark, `https://www.dst.dk/klassifikationsbilag/b7fcd3f6-eb5b-4f8d-bd22-8432ab9aee31csv_da`.

[1] The 69-grouping is the lowest level where the capital stock is accounted for.

[2] The 117-grouping is the most dis-aggregate level in the National Accounts.

[3] The DB07 is the national version of EU's nomenclature and describes the most dis-aggregate industry definition but official statistics are rarely available at this level.

* DB07 industries not included here because they are not relevant for the GreenREFORM model.

only 4.9% of the Danish Gross Domestic Product (GDP) in 2018, which is down by 1%-point since 2010.[5]

Figure 2.1 further decompose the transportation industry's GVA (Gross Value Added) into the five sub-industries listed in the 69-grouping: Land-, water-, air transportation, support activities, and postal and courier services. In 2016, land transportation is the largest industry accounting for 35%, closely followed by water transport and support activities.

Transport activity in physical terms can generally be measured in passenger- or tonne-kilometers (commonly denoted traffic work) or vehicle kilometers: While traffic work measures the activity associated with moving passengers and goods around in the economy, vehicle kilometers are typically used in describing the environmental effects of transportation.[6] The distinction is potentially important when reporting the development of transportation activity in the economy. For instance, between 2010-2019 national freight transportation with trucks have increased by 15.1% when measured in traffic work; if measured in vehicle kilometers, however, national freight transportation with trucks have decreased by 1.4%. Consequently, trucks have driven fewer kilometers but the average load per trip has increased.

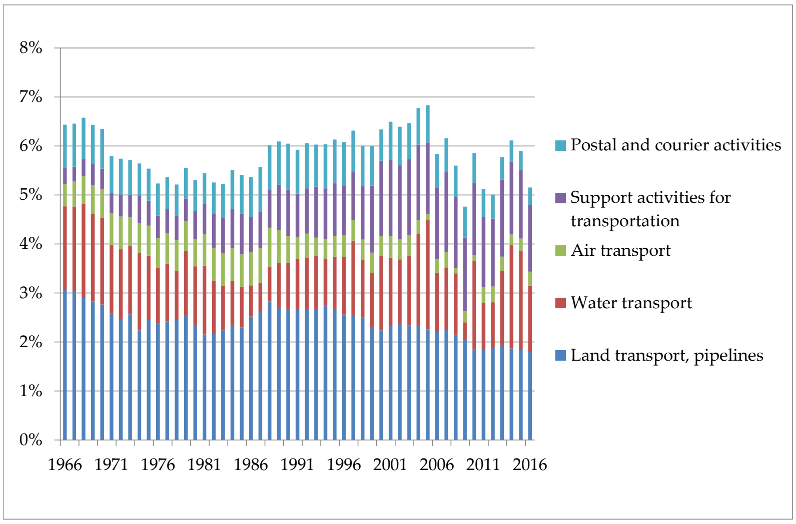


Figure 2.1: Transport sub-industries share of total GVA, 2010-2018.

Source: Own calculations based on Statbank Denmark, table NABP36.

It is important to clarify that the GreenREFORM model focuses exclusively on the latter measure because the focus of GreenREFORM is the environmental effects of transportation. Accounting for both measures is too high dimensional in a large-scale computable general equilibrium (CGE) model like GreenREFORM. For all transported goods in the economy, it would be necessary to keep account of their volumetric weight, and for this reason the dimension of the number of passengers or tonne-goods per trip is neglected.

What is common for the two measures, however, is that for hire transportation accounts for an increasing share of total national freight transportation with trucks, see figure 2.2. This pattern of an increasing outsourcing of transportation services is something that GreenREFORM should replicate.

[5]Statistics Denmark, table NABP36.

[6]Although emission coefficients depend on the occupancy/load factor of the vehicle, emission coefficients are typically only available as emissions per vehicle kilometers. See Winther (2018) for the official Danish inventory of emissions from mobile sources and associated emission coefficients.

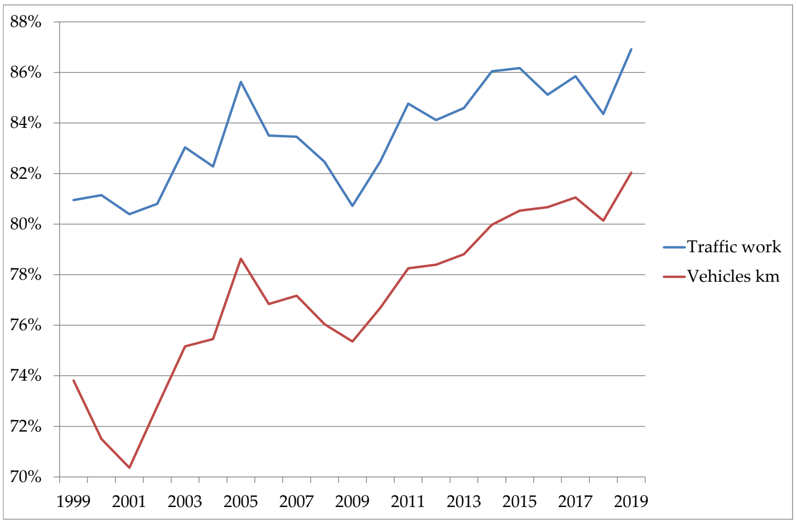


Figure 2.2: Share of for hire national transportation with trucks of total national transportation with trucks.

Source: Own calculations based on Statbank Denmark, table NVG1.

2.1 Vehicle fleet

Figure 2.3 illustrates the development in the stock of buses, passenger cars, vans and trucks (lorries and road tractors combined). While the stock of all vehicle types increased up until 2007[7], only the stock of passenger cars have increased after 2007. It is also possible to look at the vehicle stock across industries in monetary values. The Danish National Accounts distinguish between seven types of capital including transport equipment, distributed across industries on the 69-grouping. First, the transportation industry's share of total transportation capital in 2018 is 48%. According to figure 2.4a, this significant share is primarily due to the value of ships used in the water transportation industry accounting for 33% of transportation capital in the economy. Excluding water transportation implies the remaining transportation industries accounts for 23% of total transportation capital. Figure 2.4a further illustrates the importance of leasing firms, which accounts for 14% of transportation capital. Section 5 eloborates on how this observation is used in modeling investment in new vehicles.

A particular challenge in transitioning the transportation sector is to replace the current stock of fossil-based vehicles with vehicles using alternative fuels. However, looking at the development in the market share of the dominant propellant (gasoline or diesel) within vehicle types in figure 2.5, this indicator has been relatively stable the last 26 years. Only within passenger cars has the dominant propellant (gasoline) been replaced with an alternative fuel (diesel). Note, however, that the stock of diesel cars has increased in the period, while the stock of gasoline cars has just increased less.

The inertia in the composition of the vehicle fleet is essential for economic analyses of transportation policy measures. Section 5 describes how investment in new vehicles is modeled in the GreenREFORM model.

[7]Fleet data for road tractors is only available from 2007.

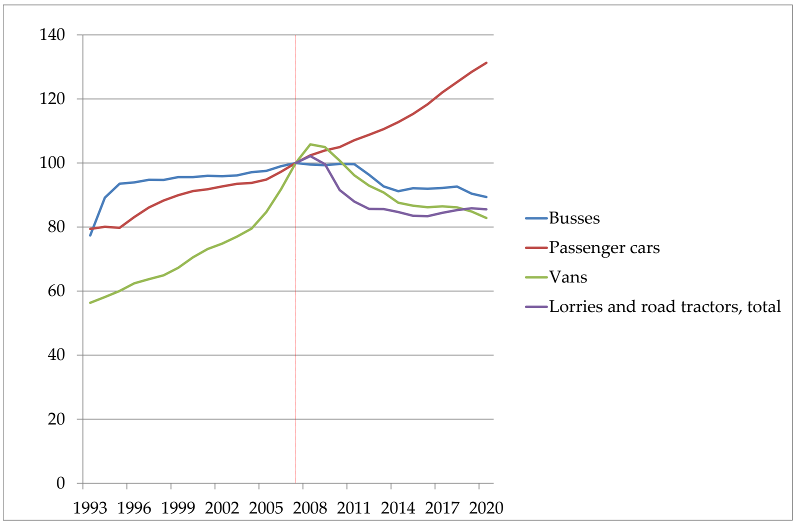


Figure 2.3: Development in the stock of vehicles across different types

Source: Own calculations based on Statbank Denmark, table BIL10, BIL12, BIL15, and BIL707.
Note: Index year is 2007 because fleet data for road tractors is only available from 2007.

(a) Including the water- and air transportation industry. **(b)** Excluding the water- and air transportation industry.

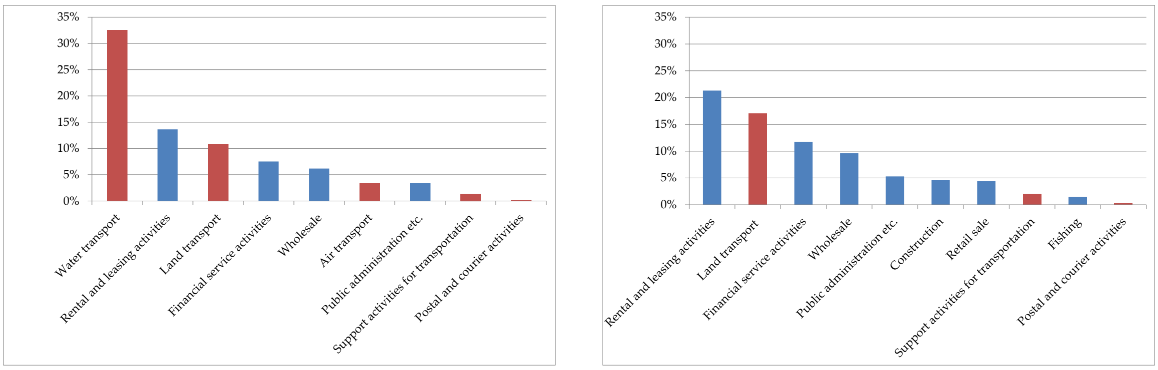


Figure 2.4: Distribution of stock of transportation capital.

Source: Own calculations based on Statbank Denmark, table NABK69.

2.2 Energy consumption

While the transportation industry accounts for less than 5% of the Danish GDP, it is far larger in terms of energy consumption. It accounts for 64% of Danish firms' total energy consumption in 2019. If emissions from households are included as well, the transportation still accounts for 48% of total Danish energy consumption.[8] Part (a) of figure 2.6 illustrates the share of energy consumption related to transportation of total energy consumption. This share has been steadily increasing since 2005 and in 2019 it was 11%, 65%, and 52% of total energy consumption for, respectively, households, industries, and both industries and households. It is important to note that these numbers are based on the principles of the National Accounts: All resources used and produced by Danish economic activity are included in the National Accounts. This is particularly important for transportation because international transport - domestic vehicles operated abroad - is included.

[8]Own calculations based on Statistics Denmark, table ENE3H.

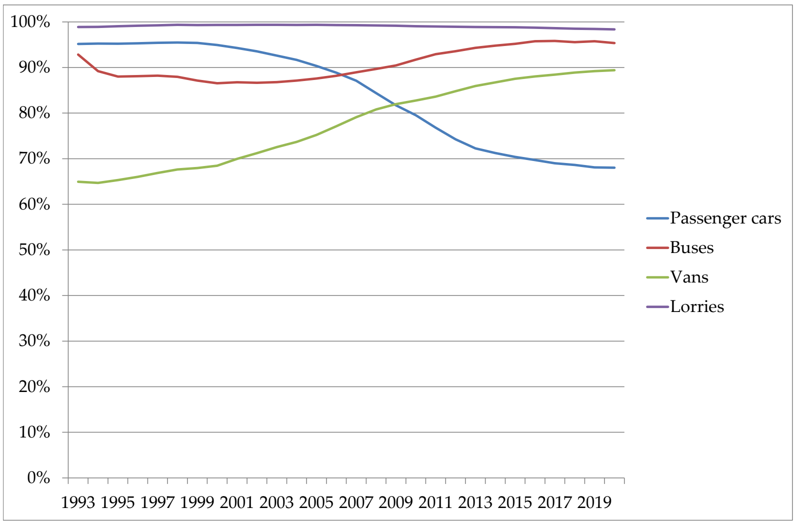


Figure 2.5: Market share of the dominant propellant within different vehicle types.

Source: Own calculations based on Statbank Denmark, table BIL10, BIL12, BIL15, and BIL18.
Note: For passenger cars the dominant propellant is gasoline and for all other vehicle types it is diesel.

Part (b) of figure 2.6 illustrates the same measure but for international transportation being excluded. In this case, the share of transport-related energy consumption of total energy consumption was 11%, 21%, and 17% in 2019 for households, industries, and both industries and households, respectively. This distinction is very important when measuring greenhouse gasses from the transportation sector and elaborated upon in section 3.1.

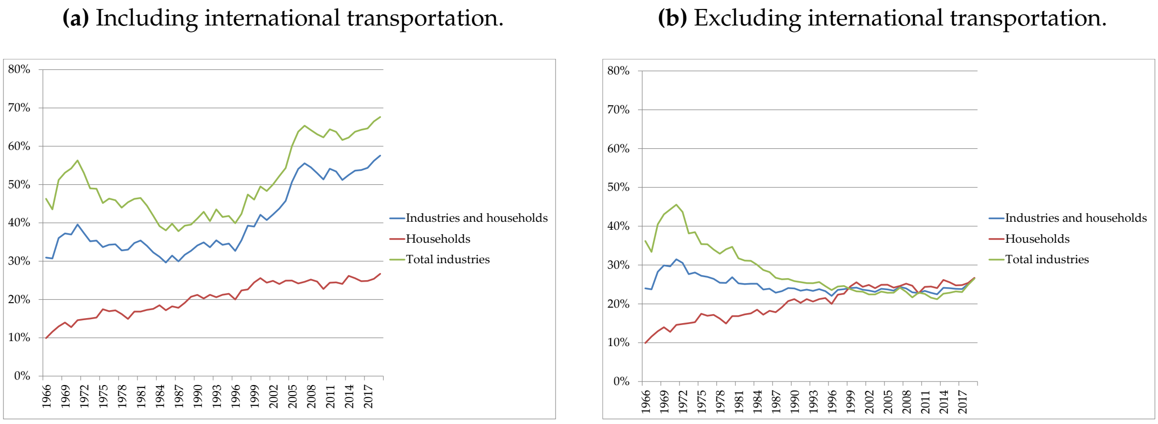
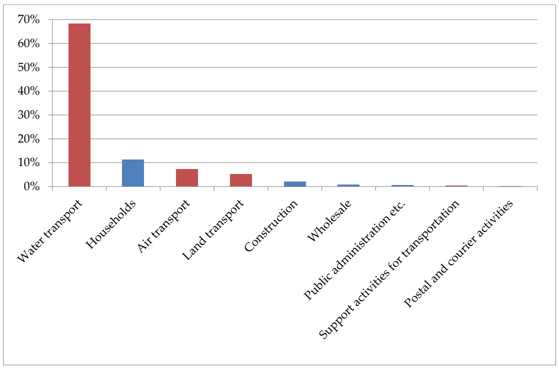


Figure 2.6: Energy consumption from transportation as a share of total energy consumption.

Source: Own calculations based on Statbank Denmark, table ENE3H.
Note: Energy consumption is defined as gross energy consumption measured in gigajoule. Transport related energy consumption is the sum of LPG for transport, jet fuel, diesel oil for road transport, fuel oil.

Finally, it is interesting to look at energy consumption from transportation across different industries. Part (a) of figure 2.7 plots consumption of diesel and gasoline in GJ on domestic territory for the transportation industries and top four non-transportation industries as well as households. Water transportation accounts for almost 70% of domestic energy consumption related to transportation. However, when excluding international transportation water transportation accounts for less than 1%. This is illustrated in part (b) of figure 2.7. In stead, households' energy consumption for transportation accounts for just over 43% when we only look at energy consumption on domestic territory. It should also be noticed that the only three industries that provide international road transportation are freight transportation (for hire), support activities for transportation (for hire), and the wholesale sector (for own account). Finally, passenger and freight air transport provide international air transport, and passenger water transport and shipping also provide international water transport.

(a) Including international transportation.



(b) Excluding international transportation.

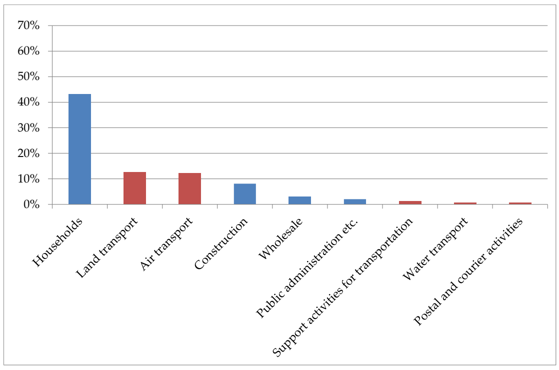


Figure 2.7: Transport related energy consumption.

Source: Own calculations based on Statbank Denmark, table ENE3H.
Note: Energy consumption is defined as gross energy consumption measured in gigajoule. Transport related energy consumption is the sum of LPG for transport, motor gasoline, jet fuel, diesel oil for road transport, fuel oil.

3 Transportation and the Environment

In the following, GHG emissions from the transportation industry are presented along with two different accounting principles for making national emission inventories. This is highly relevant for the transportation sector. Finally, the section also mentions other external effects from transportation.

3.1 GHG emissions and accounting principles

In this section, the two different principles for making an inventory of a country's GHG emissions are discussed. Further, it is shown that these two methods provide widely different estimations of Danish GHG emissions due to international transportation.

Accounting principles. We generally distinguish between two different methods for measuring GHG emissions: the United Nations Framework Convention on Climate Change (UNFCCC) and the System of Environmental-Economic Accounting – Central Framework (SEEA CF) principles. While Danish targets of reducing GHG emissions from 1990-levels are based on the UNFCCC principles, the SEEA CF principles form the basis of the Danish Green National Accounts (Gravgård et al., 2018). The UNFCCC inventory is based on a territorial demarcation and includes all emissions generated within the borders of the country. Emissions from foreign-owned vehicles operating on Danish territory are therefore also included in the UNFCCC inventory. However, emissions generated by domestically owned vehicles abroad are not included. Furthermore, GHG emissions generated from the fuel consumption of biomass is also excluded from the UNFCCC inventory. The Green National Accounts are based on the same principles as the conventional National Accounts and therefore include all emissions generated by domestic economic activity; this also covers domestically owned vehicles operating abroad but excludes foreign-owned vehicles operating on domestic territory (Gravgård et al., 2018).

Danish emissions. For many countries these methods yield similar estimates, but in the case of Denmark, they yield widely different estimates of greenhouse gas emissions. The discrepancy is illustrated in figure 3.1. First, greenhouse gasses from Danish economic activity (i.e. emissions based on SEEA CF principles) have increased by 5% from 82.4 million tonnes of CO_2-e in 1990 to 86.6 million tonnes in 2017. Of these, the share of greenhouse gasses from international transport has increased from 12% to 46% in the same period. This is mainly due to the increase in emissions from ships bunkering abroad, which accounts for 45% of emissions from international transport in 2017. Finally, by subtracting other differences from transport and cross-border trade[9], one gets the estimate based on the UNFCCC principles for which greenhouse gasses have droped by 33% from 70.2% million tonnes to 47.4 million tonnes. Denmark's goal of reducing greenhouse gas emissions by 70% in 2030 compared to 1990 is based on the UNFCCC inventory.

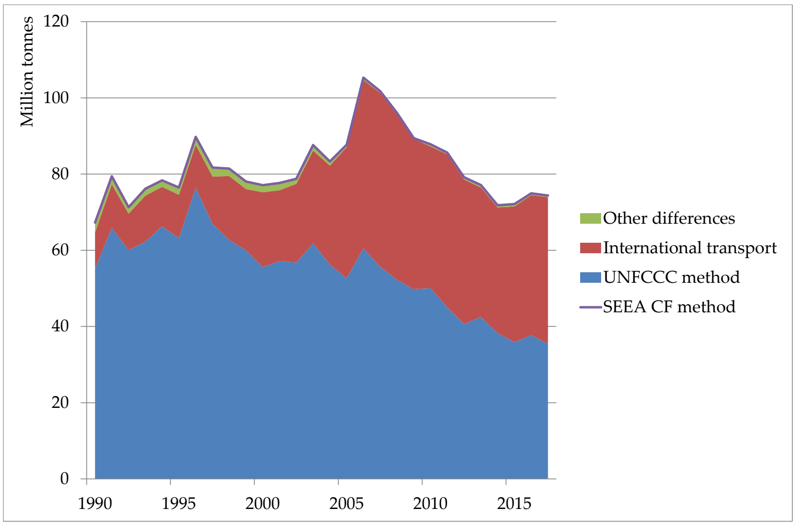


Figure 3.1: Greenhouse gas inventories according to UNFCCC and SEEA CF from 1990-2017.

Source: Own calculations based on Statbank Denmark, table MRO01.
Note: Emissions are the sum of carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) measured in CO_2-equivalents. Furthermore, emissions from the consumption of biomass-based energy is not included.

Relevance for GreenREFORM. In order to account for the development in both GHG inventories, the GreenREFORM model should distinguish between domestic and international transportation services. There are generally two approaches to modeling domestic and international transportation. First, a firm in the transportation sector can be viewed as jointly supplying both domestic and international transportation services. This has the advantage of not increasing the number of industries in the model. The second option is to split industries supplying both domestic and international transportation services

[9]Other differences in emissions from transport and cross-border trade includes bunkering of Danish ships in Danish ports for international shipping.

into two industries. While it is relatively straightforward to implement both of these methods in the existing framework, the primary challenge is that the National Accounts statistics (in contrast to the Green National Accounts) do not distinguish between international and domestic transportation. Assumptions regarding the split between domestic and international transportation are needed in order to fit the National Accounts to the model structure. Future work will focus on how the National Accounts can be appropriately adapted to include a distinction between domestic and international transportation.

3.2 Other externalities from transportation

GHG emissions are not the only externalities related to the consumption of transportation services. Other externalities include pollution (i.e. environmental effects), congestion effects, accidents, noise and wear and tear of infrastructure. Emission coefficients for NO_X (total nitrogen oxides) , SO_2 (sulfur dioxide), CO (carbon monoxide), and particles (PM_{10} and $PM_{2.5}$) are available for the current vehicle fleet. The bottom-up data, however, only contains emission coefficients for NOX, SO_2, and particles, implying that emissions of CO from future vehicle technologies are currently not included in the model. While congestion effects are expected to be included in a future version of GreenREFORM, accidents, noise and wear and tear of infrastructure are abstracted from in the GreenREFORM model. The Chairmanship of the Danish Economic Councils (2018) reported that the largest share of the total marginal external cost of driving in passenger cars is constituted of accidents and congestion effects. Of course this conclusion depends of the assumption of the marginal willingness to pay to avoid these externalities but it does highlight that pollution and greenhouse gasses are not the only externalities from transportation.

4 Upstream processes and fuel products

This section discusses upstream processes relevant for determining the technological possibilities and marginal costs of abating emissions from the combustion of fuels for transportation. These upstream processes relates to the value chain of fuels, i.e. from the extraction of primary energy and production of feedstocks to the distribution of fuels via a network of refueling stations.

Technological substitution can essentially happen in two dimensions: Either current vehicle technologies running on fossil-based fuels can be replaced with alternative vehicle technologies running on alternative propellants, or it is also possible to use a "greener" substitute for the fossil-based fuel in the existing fleet of vehicles. For instance, as an alternative to replacing petrol- and diesel passenger cars with electric ones, it might be more cost-efficient (at least in the short run) to simply use more bio-ethanol or bio-diesel without replacing the existing fleet of vehicles.[10] In some instances there may not even exist alternative vehicle technologies that are commercially viable in the foreseeable future. Heavy land-, sea-, and air transportation are expected to rely on conventional vehicle technologies in the foreseeable future and these areas of the transportation sector are more likely to rely on green counterparts of the

[10]An important discussion related to the use of bio-fuels concerns how the bio-fuels are produced. This is commented on in section **??**.

already available fossil-based fuels. Either way, it is necessary to account for both the economic costs and external effects in the entire fuel supply chain in order to determine the marginal abatement cost. Importantly, external effects are not limited to climate- and environmental-related effects in this context, because network effects may influence the speed of adoption of alternative vehicle technologies.

The value chain of fuels consists of five steps illustrated in figure 4.1: In the first step, primary energy is extracted and feedstocks are produced. In the second step, primary energy and feedstocks are delivered to so-called primary energy conversion plants, which produce either a fuel product or an intermediate energy product, needing further processing. If an intermediate product is produced, intermediate conversion plants transform it into a fuel product in the third step. In the fourth step, fuel products are (potentially) mixed together with each other, creating a final (mixed) fuel product. In the fifth and final step the (mixed) fuel product is distributed to end-consumers via a network of spatially distributed refueling stations.

Below, each step in the value chain as well as their relevance for transitioning the transportation sector to a fossil free society is elaborated.

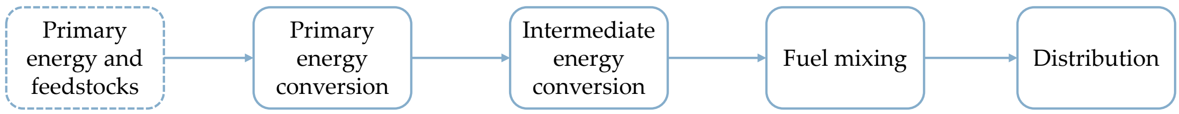


Figure 4.1: Stylized value chain of fuels.

Source: Adapted from Danish Energy Agency (2016).
Note: Primary energy and feedstocks are marked with a dotted line, because it is not part of model for transportation.

4.1 Primary energy and feedstocks

In the first step, primary energy and feedstocks are collected. Fossil-based primary energy sources such as crude oil and natural gas areii extracted by the oil and gas extraction industry. Renewable primary energy sources such as wind and solar are not associated with any economic activity but enter the second step directly. The agricultural and forestry industry also produce bio-based energy sources. For instance, the agricultural industry produces feedstocks and residual products and the forestry industry delivers wood products.

4.2 Primary energy conversion

Primary energy conversion technologies produce a range energy goods that can be categorized into fossil fuels, bio-fuels and electricity.

Fossil fuels. The oil and gas extraction industry delivers crude oil to the refinery industry and natural gas to the gas supply industry. In the refinery industry, refinery plants convert crude oil into the liquid transportation fuels petrol, diesel, heavy fuel oil, and jet fuel. The natural gas is supplied directly to the natural gas grid without any refining process. As such, no primary conversion technologies are associated with the production of natural gas[11].

Bio-fuels. Primary energy conversion plants also produce bio-fuels, which are are generally categorized into first-, second- and third generation bio-fuels, depending on the the feedstock used in the production (Nanda et al., 2018). First generation bio-fuels are produced on agricultural feedstocks that alternatively could have been used in food or as feed, e.g. ethanol produced from corn and distillers grain or FAME[12] (Fatty Acid Methyl Esters) bio-diesel as well as first generation HVO (Hydrotreated Vegetable Oil) diesel. Second generation bio-fuels are fuels produced from non-food biological materials. For instance, ethanol, bio-diesel, and bio-jet fuel can be produced on straw. Finally, third generation bio-fuels are produced from algae, sewage sludge, and municipal solid wastes but these are very much at the laboratory stage.

Bio-fuels consist of both liquid and gaseous fuels. For instance, the gas supply industry produces upgraded biogas[13], which is a substitute for natural gas and can be injected into the natural gas grid. Conversely, the refinery industry produces liquid bio-fuels, which can be substitutes to liquid fossil fuels (e.g. HVO diesel and fossil diesel) and or require a different vehicle technology (e.g. bio-methanol produced from biomass-to-liquid technologies used in cars with methanol fuel cells).

Electricity. Primary energy conversion plants can also be electricity producers. These plants are described in Berg & Eskildsen (2019). The produced electricity can both enter the electricity grid as a final fuel product to be used in e.g. electrical vehicles or the electricity is converted by intermediate conversion plants in the third step of the value chain.

4.3 Intermediate energy convsion

Fuels that are produced in the intermediate energy conversion step are generally CNG (Compressed Natural Gas) and LNG (Liquefied Natural Gas) and their bio-based counterparts, CBG (Compressed BiogGas) and LBG (Liquefied Biogas), respectively. In the future, however, fuels going through intermediate energy conversion step will also be synthetic fuels. These are described below. Compressed gas can be be tapped directly from the natural gas grid and compressed at an CNG/CBG refueling station. Similarly, liquefied gas can be made from natural gas/biogas by cooling the gas into liquefied form. Note that the process of cooling the gas into a liquefied form is done by firms located in the refinery industry.

Synthetic fuels. Synthetic fuels are produced by PtX technologies by combining hydrogen with either CO_2 or N_2 (nitrogen). The Danish transmission system operator, Energinet, and Danish Energy recently published a report on the potential for PtX in Denmark (Energinet & Dansk Energi, 2020) that highlighted the importance of PtX in delivering green fuel to the parts of the economy that cannot be

[11]The supply of natural gas is mainly associated with extraction, storage, and distribution of the gas.

[12]FAME bio-diesel are all diesel products produced by transesterification of vegetable oils. An example hereof is RME (Rapeseed Oil Methyl Esters) produced by transesterification of rapeseed oil with methanol.

[13]Upgraded biogas refers to biogas converted to natural gas quality by e.g. via anaerobic digestion.

directly electrified. The attractiveness of e-fuels is that they are not technically different from their fossil based counterparts and are therefore often a direct substitute to conventional fuels. In other words, they can be sold via the existing fuel distribution network (either as a direct substitute or blended together with the fossil based counterpart) and can in be used in conventional internal combustion cars.

Multiple technologies exist for converting power into the wide varieties of X. These are illustrated in figure 4.2. First, common for all synthetic fuels is that hydrogen is produced by electrolysis of water with (preferably renewable) electricity; a process commonly referred to as power-to-hydrogen. The e-hydrogen product can be directly used in hydrogen vehicles but can also be applied in synthesizing other fuels. For instance, by combining the e-hydrogen with CO_2 in e.g. a Fischer-Tropsch synthesis, e-fuels[14] can be produced. The CO_2 can be captured from either point sources or via DAC (Direct Air Capture). While DAC is not expected to be a vialable solution in the foreseeable future, some point sources are available already today. For instance, the production of biogas is associated with the capture of CO_2, which can then be used in producing e-Methane and e-Fuels. Similarly, CSS (Carbon Capture and Storage) technologies can be used in capturing CO_2 from e.g. flue gas. While e-fuels have many applications in rail transportation, road vehicles and air transportation, e-methane is primarily a substitute for natural gas and has to be converted into e-CNG og e-LNG. Finally, the e-hydrogen can be combined with nitrogen in a Habor-Bosch synthesis process to produce e-ammonia, which is a substitute to heavy fuel oil used in shipping.

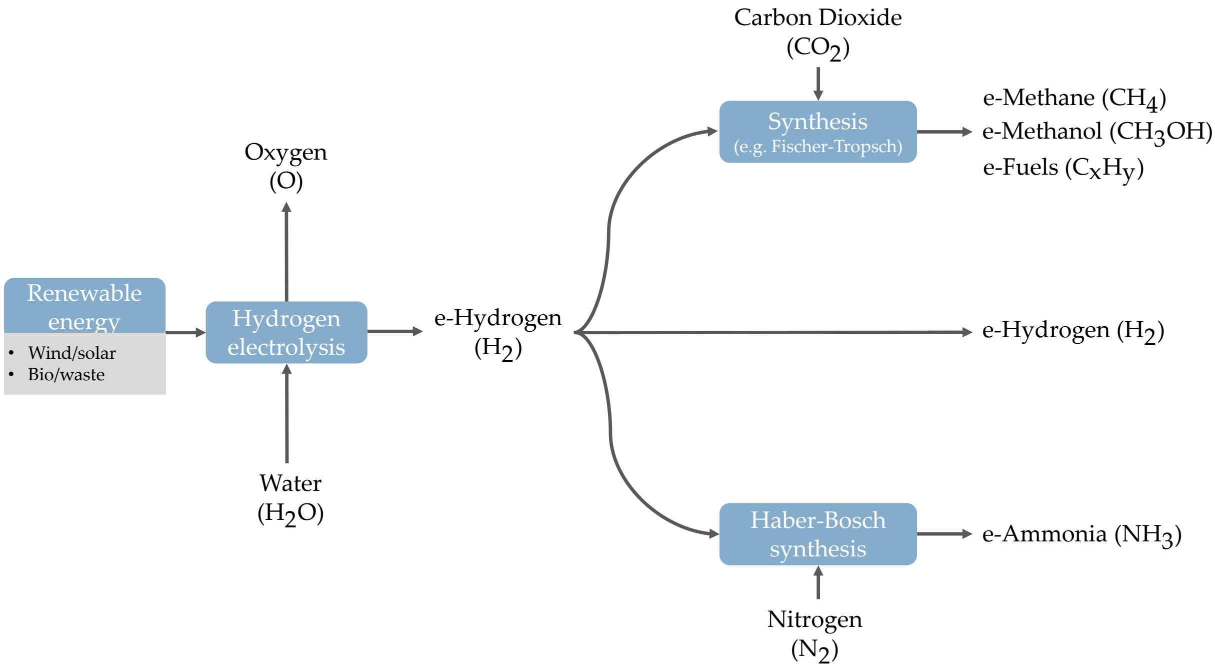


Figure 4.2: Power-to-X pathways

Source: Adapted from Energinet & Dansk Energi (2020); Isles (n.d.); Yugo & Soler (2019).
Note: E-fuels include all (liquid) fuels with the formula C_xH_y (where $x, y > 0$) such as e-diesel. This classification of e-fuels further refers to fuels produced exclusively by Fischer-Tropsch synthesis. For instance, e-methanol is produced using methanol synthesis and e-methane is produced using the Sabatier synthesis process.

[14] E-fuels include include all fuels with the formula C_xH_y, where $x, y > 0$. This includes e.g. e-diesel, and e-jet fuel. This classification of e-fuels also refers to fuels produced exclusively by Fischer-Tropsch synthesis.

PtX is, however, still an early technology with many unresolved issues. First, considerable infrastructure investments are needed in order to supply fuels based on PtX (Energinet & Dansk Energi, 2020). Second, technical standards limits the applications of PtX fuels. There is currently limited applications of e-methanol in the transportation sector because only 3% can be mixed with fossil gasoline and very few methanol fuel cell cars are present in the vehicle fleet. Third, bio-fuels currently count as 100% fossil free although they rarely are; especially if one includes ILUC (Indirect Land Use Change) effects. Bio-fuels based on vegetable oil often indirectly lead to deforestation elsewhere on the planet, thereby lowering their CO_2 displacements (Drivkraft Danmark, 2019). This distorts the incentive to invest in PtX technologies compared to bio-fuels.

4.4 Fuel mixing

As mentioned above, fuel suppliers can also mix fossil fuels with bio-fuels or synthetic fuels. The intuition for fuel mixing is that vehicles should run on cleaner fuels compatible with the current engine specifications. In Denmark this is predominately achieved by increasing the share of bio-fuels mixed with fossil fuel.

Fuel mixing is the product of command-and-control regulation imposed on fuel suppliers. Denmark has imposed national regulation, making it compulsory that at least 7.6% (energy content) of gasoline, diesel and gas for land transportation should consist of bio-fuels in 2020. Up to 2019 the share of bio-fuels was at least 5.75%-energy and will be set af 5.75%-energy from 2021 again. In order to promote second generation bio-fuels, the amount of these counts twice in the fuel share.

At the EU-level, the Fuel Quality Directive defines the allowed carbon footprint of gasoline and diesel used in land transportation. The Directive regulates the carbon footprint by obligating European fuel suppliers to reduce the GHG emission intensity of automotive fuels by 6% in 2020 compared to 2010. The measure of GHG intensity includes all GHG emissions in the fuels' life cycle from extraction, processing and distribution (well to tank).[15] Fuel suppliers generally have two strategies for meeting the 6% reduction requirement: First, they can increase the share of biofuels. Second, they can make upstream emission reductions (UERs) by lowering e.g. process emissions from extracting and refining the fuel. In this regard, the Directive also states that fuel suppliers may trade UERs to reach the target in 2020. However, since the target is only set for 2020 - with no agreed upon target post 2020 - there has been no real incentive to set up a platform for trading UERs.

Importantly, these two command-and-control regulations impose two occasionally binding constraints on fuel suppliers. While the EU regulation imposes an upper bound on the life-cycle carbon footprint, the national regulation imposes a lower bound on the share of biofuels mixed with fossil fuels.

Fuel suppliers are also restricted by technical fuel standards, which effectively impose an upper bound on the share of bio-fuels mixed together with fossil fuels. For instance, the EN 590 standard prescribes that maximum 7%-volume FAME bio-diesel can be mixed with fossil diesel. This fuel product

[15] The 2010 baseline is currently set at 94.1 g CO_{2eq} per MJ fuel.

is labelled B7 at refueling stations to indicate that up to 7&-volume consists of bio-diesel. This is contrary to HVO diesel that is approved under the standard EN 15940 and can be used clean. Likewise, maximum shares of bio-fuels apply for gasoline. In Denmark, E5 and E10 is sold at refueling stations where e.g. E5 indicates that fossil gasoline is mixed together with maximum 5%-volume bio-ethanol.

4.5 Fuel distribution network

The diffusion of alternative fuels and new zero-emission vehicles also depends on the availability of refueling stations. Such effects are commonly referred to as indirect network effects.

Positive network effects arise when the utility that a user derives from the consumption of a good is increasing with the number of other agents consuming the good (Katz & Shapiro, 1985). The externality arises when agents do not internalize the network effect and the decentralized economy does not capture all social benefits (?, ?). A general distinction is made between direct and indirect network effects: Direct network effects refers to a situation in which consumers' utility and incentives to adopt a good increases as other users adopt the good. Indirect network effects arises if other consumers use of the good increases the supply of complementary services, making the good more valuable to the individual consumer (?, ?). Propellant distribution networks belong to the latter: More users of a given network of refueling stations provides incentives for station owners to increase the network density, which in turn increase the value (utility/productivity) of the vehicle itself. The important normative question is whether this indirect network effect leads to adoption externalities, i.e. whether or not an individual consumer's use of a certain vehicle technology increases the incentive of other consumers to adopt the technology, without the individual consumer internalizing this effect. If a positive adoption externality is present, the diffusion of green technologies exhibits excess inertia.

In analyzing hardware/software systems Church et al. (2008) provide three general conditions under which indirect network effects may give rise to positive adoption externalities: (i) there is increasing returns to scale in the production of software, (ii) free entry in software, and (iii) consumers have a preference for software variety. This result is also relevant for vehicle adoption given that vehicles and fuel distribution network also falls under the hardware/software terminology.[16]. The intuition for the result - in the context of vehicles - is that the private benefit of the vehicle consumer on the margin is less than the social benefit because marginal consumer does not internalize, that more vehicles induces the the fuel distribution industry to increase the number of refueling stations. This in turn benefits inframarginal vehicle consumers. They argue that the taste for variety[17]. is a key factor required for indirect effect to lead to adoption externalities. In the present context, the taste for variety represents the preferences for a more dense network of refueling stations.

The presence of positive indirect network effects have been documented empirically for electrical vehicles (see Zhang et al., 2016; S. Li et al., 2017; J. Li, 2019; Springel, 2019) but it is generally recognized

[16]"Hardware/software" is a general terminology that apply to many markets, such as credit-card networks (merchant acceptance it the software and the credit-card is the hardware) and durable equipment and equipment services (the durable good is the hardware and the equipment services are the software).

[17]The taste for variety is a concept leading all the back to Dixit & Stiglitz (1977).

that such network effects also exist for other alternative fuels: The EU has adopted the Alternative Fuels Infrastructure Directive, which requires member states to - amongst others - develop a national policy framework for the development of alternative fuels and their infrastructure.

Fuel distribution networks are important due to the policy implications of network externalities. Acemoglu et al. (2012) argues that subsidies may be necessary to avoid the excessive use of carbon taxes due to positive externalities affecting the diffusion of green technologies. Consequently, carbon taxes should potentially be complemented with subsidies to infrastructure development in order to decrease emissions.

5 The transport model in GreenREFORM: An introduction

This section provides an introduction to the transportation model and the components that will be implemented by an internal project deadline of November 1, 2020. The section is meant to provide an overview of the transportation module and explain the intuition behind the choices made. First, the disaggregation of the transportation sector is described along with the transportation services included in the model. Besides modeling the transportation sector, the model also includes a detailed account of industries producing the transportation fuels. The modeling of these upstream processes is also discussed.

5.1 The transportation sector

In the GreenREFORM model, the transportation sector consists of (for hire) transportation industries in the transportation industry, (for own) transportation services within non-transportation industries, and households' private transportation services.

Transportation industries. The transportation model relies on a dis-aggregated version of the National Account's 117 industry grouping. This allows a detailed breakdown of various modes of transportation, implying that the transportation model has twelve transportation industries besides support activities for transportation and post and courier services (fourteen in total). This should be compared to the seven transportation industries in the 117 industry grouping in the National Accounts. The fourteen industries are listed in table 2.

The overall purpose of the division of industries is to appropiately capture the heterogeneity of transportation services, and this has been done on the basis of four dimensions: First, the categorization should distinguish between passengers and goods being transported because this defines the overall purpose of the transportation activity. Second, the industry categorization should capture the most important modes of transportation and the differences between them. The main modes of transportation to distinguish between are rail-, road-, water-, and air transportation. Third, the division should allow a crude characterization of travel distance related to the different modes of transportation, as travel distance is important in specifying an appropriate pattern of substitutability between the different modes of transportation. For instance, urban modes of transportation are not substitutable with interurban modes of transportation. An example hereof is that urban and suburban buses do not compete with interurban buses in supplying passenger transportation services; rather, they compete with S-trains, metro, taxi and private modes of transportation (e.g. bicycle). Fourth and final, the division should capture the main regulatory differences. For instance, within urban modes of transportation, the regulations of buses and taxi are widely different.

Table 2: Transportation industries in the GreenREFORM model

GreenREFORM indusrty	**DB07 industry**[a]	
	nr.	label
Interurban passenger rail	49.10.00	Interurban passenger rail transport
Interurban freight rail	49.20.00	Interurban freight rail transport
Interurban buses	49.39.10	Interurban buses and school buses
Coaches	49.39.20	Coaches and other land passenger transport
Urban and suburban buses	49.31.10	Urban & suburban buses
S-trains and metro	49.31.20	S-trains and metro
Taxi	49.32.00	Taxi
Road freight	49.41.00	Freight road transport
	49.42.00	Moving companies
Ferries	50.10.00	Sea and coastal passenger transport
	50.30.00	Passenger transport by inland waterways
Shipping	50.20.00	Sea and coastal freight transport
	50.40.00	Freight transport by inland waterways
Passenger air	51.10.10	Scheduled passenger flights
	51.10.20	Charter & and taxi flights
Freight air	51.21.00	Air freight transport
Support activities for transportation	52.00.0[b]	Support activities for transportation[b]
Post and courier services	53.00.0[b]	Post and courier activities[b]

[a] The DB07 is the national version of EU's nomenclature and describes the most dis-aggregate industry definition.
[b] This is according to the 117 industry grouping in the National Accounts. All sub industries in DB07 with this 117-industry is included.

Finally, it should be noted that post and courier services are currently grouped together, which might pose a problem for two reasons: First, postal services are under the universal services obligation and therefore differently regulated compared to courier services. Second, it is a well know phenomenon that postal services under the universal service obligation are declining due to electronic substitution.[18] Conversely, courier services are increasing due to e-commerce (Almqvist et al., 2018). If GreenREFORM should be used for general equilibrium analysis of postal sector regulation and the impact of e-commerce on GHG emissions, these two industries should ideally be separated.

[18]Electronic substitution refers to the process of traditional letter post communication being replaced by electronic means of communication (e.g. email).

Households. Currently, households' own transportation consists entirely of private passenger car transportation and two-wheelers. In future versions of the model, it is expected that bicycle/walk will be added to households' private transportation services, which will substitute with other urban modes of transportation. Bicycle/walk will not be included per November 1, because its primary cost component is the value of the time it takes to make the trip. Time spent on transportation, however, will only be added to the model in future versions.

For own transportation. Non-transportation industries also supply for own transportation services as part of their logistical operations. It is not the intention of the transportation model to describe the purpose of these industries' internal transportation services (i.e. passenger/freight) but to capture an aggregated input of transportation services on the basis of the industry's vehicle fleet, which substitutes with outsourced transportation services. Consequently, although vehicles of different vintages and technologies within non-transportation industries can be identified, the service a given vehicle provide cannot be identified. For this reasons, all vehicles contributes to an aggregate input of transportation services.

Vehicle fleet. What is common to all industries and households is that they use a distribution of vehicles in order to supply transportation services. While the division of transportation industries allows abatement of emission via substitution to low-emission transportation modes, future prospects for low emission transportation services are to a large extent determined by technological substitution within the fleet of vehicles supplying a given mode of transportation. The most obvious example is households' private car transport. While households can shift to e.g. public transportation, the emission cuts are most likely to come from gradual replacement of conventional internal combustion engines. Recognizing this aspect, the model incorporates a heterogeneous stock of vehicles. Specifically, vehicles are vintage and prime mover specific to allow for technological change in two dimensions. First, technological change in the transportation sector is embodied in new vintages from the improvements in existing technologies, where embodied technological change is primarily energy saving. Second, new prime mover technologies become available in the future and diffuse if they are cost-efficient. The current stock of vehicles is supplied by Statistics Denmark and the techno-economic potentials of future vehicle technologies are based on the bottom-up data.

Based on the invention in the National Account that households leases housing from a representative industry, the transportation model in GreenREFORM assumes that industries lease vehicles on a yearly basis from a representative leasing firm. This assumption is necessary for computational tractability.[19]

As illustrated in section 2.1, the vehicle fleet adjusts slowly over time at the aggregate level and the modeling of investment should ideally capture the considerable adjustment cost associated with replacing the current fleet of vehicles with new ones. In order to capture the rigidity of the fleet, vehicle investment is assumed to be associated with transaction cost. While transaction costs have been justified on the basis of vehicles investments being lumpy at the individual level (see e.g. Gillingham et al., 2019), transaction costs in GreenREFORM is motivated by the observation that some vehicle technologies are

[19]It reduces the dimensions of the investment problem with a factor equal to the number of industries in the GreenREFORM model.

not able to enter the market on a macroeconomic level. In other words, in a representative agent setting as in GreenREFORM, transaction costs explain why some technologies never penetrate the market.

Transaction costs are the sum of a fixed cost of investment and trade costs. The fixed cost of investment represents the indivisibility of a vehicle and implies that below a certain point of break-even, it is not profitable to invest in a certain vehicle technology. The trade cost is represented by a wedge between the purchasing and sell/scrap value of the vehicle. Such capital trade cost are also commonly referred to costly reversibility because it is costly to reverse the investment decision (Abel & Eberly, 1996). Compared to a situation with zero trade cost, it implies that the value of vehicle decreases because the option value of the vehicle decreases. This lowers investment. The transportation model in GreenREFORM goes one step further and assumes costly irreversibility; that is, the selling/scrap price of vehicles is zero. In other words, once a vehicle is purchased it has no value to the leasing firm except for its leasing value. It is consistent with the absence of a secondary market for vehicles because the leasing firm owns the vehicle throughout its lifetime and leases the vehicle on a yearly basis to industries. The assumption of costly irreversibility is crucial because it implies, that the investment problem can be numerically solved for using the same algorithm used to solve the CGE model. Otherwise, other numerical algorithms would have to be used (see e.g. Gillingham et al., 2019).[20]

The key take away from the description of vehicle investment is that adjustment lags in the vehicle fleet are imposed on the demand side on the form of transaction cost. While the model also allows for indirect network effects (see section 5.4 and how this affects the vehicle adoption), the supply of vehicles is perfectly elastic determined at the cost-prices in the bottom-up data. This is based on the assumption that Denmark is a small open economy, taking future production of vehicles as given. Hence, there are no adjustment lags in the stock of transport equipment from the supply side. The adjustment costs come exclusively from the demand side.

Vehicle choice. The choice of vehicle technologies of a given vintage is described by nested constant elasticity of substitution (CES) functions (see Keller, 1976), which are at the heart of any large-scale CGE model. The fundamental assumption is that vehicles of different vintages and technologies are imperfect substitutes, where the parameters of the nested CES functions determine the substitutability between any two vehicle technologies of a given vintage. It is important to note that the stream of transportation services generated by the use of a certain vehicle technology of a given vintage is given by the combination of the vehicle and fuel consumption. It is generally assumed that vehicles and fuels are relative complements: if the value (i.e. utility/productivity) of a certain vehicle increases, fuel consumption increases as well. In this regard, it is neither the fuel nor the vehicle in themselves that are valuable; rather it is the the stream of transportation services that is generated by the combination of the two.

[20]It is, however, possible to impose a simple rule-of-thumb for implementing endogenous scrapping in the model. The rule-of-thumb for scrapping is based on the assumption that agents scrap vehicles based on a heuristic approach.

5.2 Fuel producing plants

Fuel producing firms are represented by a set of representative technologies for producing a certain fuel. The plants are located in the (bio)refinery industry and the gas supply industry (biogas). Table 3 lists fossil fuels and their green counterparts included in the bottom-up data. Table 4 list alternative fuels to fossil ones also included in the bottom-up data.

In the bottom-up data, the fundamental characteristics of fuel producing plants are (i) a maximum output/input capacity, (ii) a rate of conversion efficiency[21], and (iii) constant unit cost of production. The modeling of upstream fuel producing plants follow (Berg & Eskildsen, 2019), which is consistent with the description of power and heat producing plants in the GreenREFORM model. (Berg & Eskildsen, 2019) assumes that marginal cost non-constant and increasing in the degree of capacity utilization. Plant managers then gradually increase capacity utilization as the unit value of their outputs exceed marginal cost of capacity utilization.

Upstream fuel producing plants also includes plants based on power-to-X technologies. The description of these technologies closely follows that of heat pumps in (Berg & Eskildsen, 2019): Whenever profitable, they buy electricity on the hourly wholesale market in order to produce the output X. As many of these power-to-X technologies are not mature, they are expected to be relatively high marginal cost, implying they are only able to operate whenever the hourly electricity price is low. It should be noted that there is still work to be donem when it come to describing power-to-X and its impact on the economy. As highlighted by Energinet & Dansk Energi (2020), there are important infrastructural considerations if power is to be used to produce hydrogen. These infrastructural consideration relates to the ways of transporting and storing hydrogen.[22] Furthermore, it has to be possible to transport hydrogen further down the value chain for it to reach the end-consumer. Finally, e-fuels based on power-to-X requires an input of CO_2. Currently, it is assumed that the only source of CO_2 comes from upgrading biogas, but a technology catalog for CCS technologies is needed in order to appropriately account for the prospects of carbon capture and power-to-X.

While these issues are currently unresolved, the Danish Energy Agency has already published a technology catalog of representative technologies for storing hydrogen.[23] and are planning to produce a catalog for carbon capture technologies. Future research will focus on utilizing these technology catalogs.

5.3 Fuel mixing

Section 4.4 outlined that fuel suppliers can mix fossil fuels with a green counterpart under the restriction that the mixed fuel product comply with technical standards. These technical standards essentially give

[21]Conversion efficiency refers to the rate at which the plant can convert energy inputs into energy outputs (both in energy units).

[22]If hydrogen is converted from renewable intermittent energy, it will be necessary to be able to store hydrogen in order to provide operating flexibility to power-to-X facilities.

[23]See `https://ens.dk/sites/ens.dk/files/Analyser/technology_data_catalogue_for_energy_storage.pdf`

Table 3: Conventional fossil based fuels and their green counterparts

Surface	**Form**	**Fossil fuel**	**Green counterpart(s)**
Passenger car, van, truck, bus	Liquid	Petrol	Bio-ethanol[a]
Passenger car, van, truck, bus	Liquid	Diesel	Bio-diesel [a]
Passenger car, van, truck, bus	Gaseous	CNG[b]	CBG [c]
Rail	Liquid	Diesel	Bio-diesel[d]
Rail	Gaseous	LNG[e]	LBG[f]
Passenger ferry	Liquid	Diesel	Bio-diesel[d]
Freight ship	Liquid	HFO[g]	Bio-diesel[d]
Freight ship	Gaseous	LNG[e]	LBG[f]
Air plane	Liquid	Jet fuel	Bio jet fuel[h]

[a] This includes both first generation ethanol products and second generation ethanol produced from straw.
[a] This include both RME (Rapeseed Oil Methyl Esters) and HVO (Hydrotreated Vegetable Oil). HVO is viewed as an direct substitute to conventional diesel under the standard EN 15940. Conversely, RME is a bio-diesel approved under the standard EN 14214. RME is subject to maximum fuel mixing shares because it is not a direct substitute to conventional diesel.
[b] Compressed natural gas.
[c] Compressed bio gas is technically similar to CNG but produced using biomass based bio-natural gas upgraded via anaerobic digestion.
[d] This consists of second generation bio-diesel made from straw.
[e] Liquified natural gas. Vehicles with Otto-cycle dual-fuel engines are able to run on a combination of LNG and diesel.¨
[f] Liquified bio gas is technically similar to LNG but produced using biomass based bio-natural gas upgraded via anaerobic digestion.
[g] Heavy fuel oil.
[h] Bio-jet fuel is a second generation fuel produced on straw.

Table 4: Alternative fuels to fossil fuels

Surface	**Form**	**Fossil fuel**
Passenger car	Liquid	Methanol[1]
Passenger car, Truck, Bus	Gaseous	DME[b]
Passenger car	Energy carrier	Hydrogen & electricity
Van, rail	Energy carrier	Electricity

[a] Fuel cell cars are able to run on methanol. The methanol can either be produced on wood or via PtX.
[b] Dimethyl ether. Can be used in diesel engines modified to run on DME. In bottom-up data, the DME is produced via biomass (wood) gasification.

rise to multiple products for a given fossil fuel product. For instance, fossil based gasoline is potentially available as E5, E10, and E85. However, it is not the aim of the model to include multiple mixed fossil based fuel products for two reasons. First, it increases the size of the model by having multiple products within a fuel type. Second, with the current data for vehicle technologies it is not possible to identify which vehicles are/will be able to use higher mix ratios of bio-fuels.

Instead, fuel suppliers are assumed to be able to mix fossil based fuels with cleaner counterparts within a given ratio. The lower bound of this ratio is given by the minimum share of bio-fuels imposed on fuel suppliers. The upper bound is given by technological restrictions. For instance, for gasoline the possibility of E85 penetrating the market is disregarded; this is consistent with the Danish Energy Agency's baseline projection and that flexi-fuel cars are never introduced into the market. Hence, the model does not allow for flexi-fuel cars nor mixing in E85 ratios. Instead, it is assumed that E5 imposes an upper bound on the share of bioethanol mixed with fossil gasoline until 2019. From 2020, E10 defines the upper bound. Note that E20 is expected to become the industry standard in the future. This can be accounted for in the model, by adjusting the upper bound in future time periods based on the expectations of industry experts [jeg har ændret denne sætning. tjek den]. For diesel, the B7 standard is used as the upper bound on the fuel mix share of FAME biodiesel, which is also consistent with the Danish Energy Agency's baseline projection.

It is assumed that an intermediate firm buys fuels (measured in energy units) from primary conversion plants or intermediate conversion plants. The intermediate firm mixes the fuels and sells the mixed product to refueling station owners, who distribute the fuel to consumers. The problem of the fuel mixing firm closely follows Kirk & Stephensen (2020): The objective of the firm is to choose an optimal portfolio of different fuels under the restriction that the sum of input fuels equal the mixed fuel (in energy units). The upper and lower bound restrictions on the share of bio-fuels are modeled as endogenously adjusting unit taxes on fossil fuels and bio-fuels that (potentially) raises the wholesale prices of the mixed fuel product. The intuition is that command-and-control regulation is costly, because it possibly refrains fuel suppliers from choosing the optimal mix of bio- and fossil fuel. Hence, it distorts the cost minimizing mix of fuels in the same manner as an indirect tax.

5.4 Fuel distribution networks and network externalities

As highlighted in section 4.5, vehicle adoption is subject to indirect network externalities. The network externalities highlight the importance of developing a fuel distribution network in order to increase the adoption of alternative fuel vehicles. The network benefit, in GreenREFORM, materializes itself as lower unit costs of fuel consumption. The interpretation is that a more dense fuel distribution network makes it logistically easier to plan daily trips.

The network model is a dynamic version of the canonical Spence-Dixit-Stiglitz model (the name is attributed to Spence, 1976 and Dixit & Stiglitz, 1977). It is based on a representative agent framework in which the agent consumes a variety of differentiated goods. In the present context, these goods are the fuel sold at spatially differentiated refueling stations, representing a network benefit. Each station owner operates one station subject to monopolistic competition, implying prices are set with a mark-up. New entrants, however, may enter the market by incurring the fixed cost setting up a refueling station. Entry therefore expands the fuel distribution network. The dynamic aspect of the model relates to the feature that the number of differentiated goods evolves dynamically over time. The dynamic structure of the network density is based on Gandal et al.'s (2000) model for the diffusion of hardware/software systems. Gandal et al. (2000) has also been applied in modeling indirect network effects in EV charging (see e.g. S. Li et al., 2017; Springel, 2019).

The Spence-Dixit-Stiglitz model is not without its limitations. It is relatively stylized as it abstracts from important questions such the locational choice of refueling stations, compatibility issues between networks and strategic decisions of potential incumbents. However, it allows a simple and tractable analysis of the network density and has been a used previously in analyzing the connection between vehicle adoption and fuel distribution networks. The simplicity of the network model is ideal because it is implemented in a large-scale CGE model.

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Appendices