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Modelling the interaction between the energy system and road freight in Norway

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ABSTRACT

By soft-linking models for transport demand, vehicle turnover and energy generation and use, we show how such models can complement each other and become more relevant and reliable policy support tools. A freight demand model is used to project commodity flows onto the 2050 horizon. An energy system model is used to map the relationships between energy prices, fiscal incentives, and optimal vehicle technologies. A stock-flow vehicle fleet model is used to calculate the time lag between innovation affecting new vehicles and the penetration of novel technology into the fleet. By running the latter two models in an iterative loop, we predict the flow of new vehicles with more or less decarbonized powertrains, contingent upon energy prices and fiscal incentives, while also obtaining a well-founded and more realistic assessment of the time needed for radical CO_2 mitigation. The methodology is illustrated through a scenario developed for Norway.

1. Introduction

A large potential for greenhouse gas abatement in transport lies in battery electrification and phasing in of hydrogen as an energy carrier for long-haul freight. In this study we focus on how linking transport and vehicle demand models to energy systems models can increase our understanding of the transition to zero and low carbon road freight transport. The models complement each other, since energy systems modelling may describe a cost optimal method of decarbonization, while stock simulation models provide more realism when it comes to the transition pace.

In this work Norway is used as an example for linking national transport demand and vehicle stock-flow models to an energy system model. The country has adopted national climate targets with emissions cuts of 80 to 95 percent by 2050 compared to 1990, which is almost in line with the European Union (EU) climate neutrality vision (European Council, 2021a, Lovdata, 2018). To comply with the international Paris agreement, Norway, together with EU, has recently adjusted a common goal of greenhouse gas cut of 50 percent by 2030 compared to 1990 (Norwegian Environment Agency, 2021). At the EU level there is an ongoing process to lay down even more ambitious targets for the sectors not encompassed by the European Union's Emissions Trading System (EU ETS), aiming at 55 percent greenhouse gas cut compared to the 2005 level within the "Fit for 55" package (European Council, 2021b). For the transport sector to reach or, at best, overshoot these targets, a transition to zero and low emission technologies is needed. Obviously, the shift of energy carrier from fossil fuel to electricity will also affect the energy market.

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Nomenclature

BEV	Battery Electric Vehicle
FCEV	Hydrogen Fuel Cell Electric Vehicle
GVW	Gross Vehicle Weight
HEV	non-plug-in hybrid vehicle
ICE	Internal Combustion Engine
LCV	Light Commercial Vehicle / Vans
OEM	Original Equipment Manufacturer
PEM	proton exchange membrane (electrolyser)
PHEV	Plug-in Hybrid Electric Vehicle
TKM	tonne-kilometres
VKM	vehicle-kilometres
ZEV	Zero Emission Vehicle

Since the late 1990s, the Norwegian government has developed and pursued an increasingly forceful policy in support of zero and low emission vehicles. The purchase of battery electric passenger cars has been strongly incentivized, through exemptions from almost all the taxes and charges applicable to cars with an internal combustion engine (ICE) (Fridstrøm, 2021). As a result, the battery and plug-in hybrid electric vehicle market shares reached 64.5 percent and 21.7 percent, respectively, of all new passenger cars in 2021, bringing the average type approval emission rate of all new passenger cars down to 27 gCO_2/km (OFV, 2021). While the electrification of passenger cars has really taken root in Norway, vans lag about five years behind, 17.1 percent of new vans being battery electric in 2021. Battery electric trucks, however, accounted for only 1.4 percent of new registrations in 2021 (Statens vegvesen, 2022).

This paper focuses on electrification of the Norwegian light and heavy duty commercial vehicles (vans and trucks). In these vehicle segments, the current fiscal incentives are much weaker, especially for trucks, which are subject to no important fiscal charges other than fuel tax and road toll.

Light commercial vehicles (LCVs, or vans) with an ICE are subject to a one-off purchase tax set at 25–30 percent of the rate defined for passenger cars (Fridstrøm et al., 2022). Zero emission vans are exempt of registration tax. Also, since 2019, a subsidy scheme is in place for battery and fuel cell electric vans, amounting to at most NOK 50 000 (=ca. € 5 000) per vehicle.

To facilitate the phasing in of low and zero emission heavy trucks, the Norwegian government offers a subsidy that covers up to 40 percent of the additional costs of investing in biogas, battery, or hydrogen powered trucks, while also supporting infrastructure for charging and hydrogen refuelling provided that these are publicly available (Enova, 2021).

To force the manufacturers to bring low carbon vehicles to the market, the EU-regulation 2019/1242 sets a CO_2 emission goal as reckoned per payload tonne kilometre (TKM) in new heavy-duty vehicles. It applies for the most common truck types in EU and aims for 15 percent reduction by 2025 and 30 percent reduction by 2030 (compared to 2019/2020). The regulation also enables increased vehicle weight up to 2 tonnes for zero emission trucks to compensate for heavier powertrain compared to ICE trucks (European Union, 2019). Norwegian legislators are in the process of making this regulation apply in Norway in the same way as in the EU (Norwegian Ministry of Transport and Comunications, 2022).

In general, electricity is the major energy carrier in Norway. In 2020, electricity consumption in all end-use sectors was 113 TWh, or 54 percent of total final energy use, and 130 TWh electricity was produced by hydro and wind power, leading to net export of electricity. It makes the country well positioned for electrification of the transport sector, which represented more than 25 percent of the Norwegian energy consumption in 2020 (52 TWh) (Statistics Norway, 2020a).

A review of various national forecasts indicates an electricity demand in the transport sector of 15 TWh by 2040 (NVE, 2021, Statnett, 2020) and a total energy demand within road transport of approx. 14 TWh in 2050 (DNV, 2021), if 90 percent of it would be electric. Hydrogen as a possible energy carrier for transport in general is mentioned in all three reports, while only the NVE (2021) specifies its possible use in heavy-duty road freight.

Earlier studies of combining transport with energy system models have focused mainly on passenger transport, with very sparse coverage of the freight transport sector. The present analysis is combining established sector models for energy and transport, respectively, highlighting the interaction between the two sectors, so as to provide improved policy support. Our contribution to the literature is a demonstration of how a combination of transport projections, a vehicle stock-flow model and an energy system model will provide more relevant and reliable results. The focus of the study has been on light commercial vehicles (LCVs, or 'vans', for short) and heavy-duty rigid trucks and tractor-trailers ('trucks', for short). Technically, vans and trucks are defined as freight vehicles with a maximally allowed gross vehicle weight (GVW) below or above 3.5 metric tonnes, respectively.

The research questions addressed in this article are twofold. First, what are the advantages a multi-model approach in the analysis of road freight decarbonization? Second, what does the multi-model approach tell us about the impacts of zero emission commercial vehicles (vans and trucks) on the energy system and on future CO_2 emissions? Our main contribution is methodological. As a demonstration, we present a scenario developed for Norway onto the 2050 horizon.

2. Literature review

2.1. Technology development

Fossil fuel has a superior volumetric and gravimetric density of energy storage, and the ICE vehicles offers a reliable and economic powertrain. The energy efficiency of ICE powered vehicles can be improved upon, but these enhancements are necessarily marginal as compared to the transition to battery electric powertrains. Biofuel has a somewhat lower energy content than fossil fuel, but has the advantage that it can be used in the ICE. However, the option of using biofuel in ICEs is limited by its cost and by the access to sustainably sourced fuel (Panoutsou et al., 2021). Biofuels can be an alternative to battery and fuel cell electric vehicles when driving range or storage density is essential (Gray et al., 2021). For BETs the cost, gravimetric energy density and lifetime of batteries have been the main constraints (Cano et al., 2018, Mareev et al., 2017). Also, the lack of infrastructure for charging and hydrogen refuelling has impeded progress towards zero-emission trucks. For fuel cell electric trucks (FCEV), the costs of hydrogen, fuel cells and hydrogen tanks will be important barriers in the competition with ICEs (Zhao et al., 2018, Kast et al., 2018). By using hydrogen as an energy carrier, a higher gravimetric density of energy storage and faster refuelling can be achieved in comparison to electric charging (Cano et al., 2018, Cunanan et al., 2021).

The development of hydrogen-powered FCEV was initiated by start-up companies, such as Nikola, and rebuilds, such as Emoss (2021), and Esoro (2022). During the last years, fuel cell trucks have gained momentum, as an original equipment manufacturer (OEM) like Hyundai already delivers hydrogen powered trucks to Switzerland (Hyundai, 2020), and the joint venture Cellcentric by Daimler and Volvo aims to accelerate hydrogen powertrain development (Volvo, 2021).

Battery electric powertrain as an option for decarbonisation of the road freight has attracted increased attention the recent years. The controversial launch of the battery electric concept truck Tesla Semi in 2017 sparked a discussion of its potential role (Tesla, 2017, Sripad and Viswanathan, 2017). Recent studies have demonstrated the important role that such trucks could fill in the transition towards decarbonizing the sector (Martín et al., 2019, Moll et al., 2020, Basma et al., 2021).

As of 2022 most of the established OEMs have begun serial production of battery-electric trucks (Volvo, 2020, Scania, 2020, Daimler, 2021, BYD, 2021), while for Tesla's Semi truck serial production is still pending.

As several of the OEMs established in Norway now offer series produced BETs, an increase in their deployment has been observed, and more than 100 electric trucks were on the Norwegian roads by the end of 2021 (Statens vegvesen, 2022, Pinchasik et al., 2021). The accelerated commercialization of BETs has given rise to discussion and scepticism concerning the role of hydrogen in the decarbonisation of trucks (Plötz, 2022).

The rapid technology development has resulted in technology pull of zero emission trucks in Norway through national and regional initiatives like the "Green Land Transport Initiative" (Grønt Landtransportprogram, 2021) and "H2Truck" (H2 Truck, 2021).

2.2. Energy and transport modelling

Until now, most studies that combine transport with energy system models have been focused on light-duty vehicles in general and on passenger cars in particular. Often the transport sector in energy system models has been described in strongly aggregate terms (Thiel et al., 2016, Brown et al., 2018, Gea-Bermúdez et al., 2021). In some energy system modelling exercises the vehicle segment is disaggregated to represent trucks separately (Helgeson and Peter, 2020, Capros et al., 2019), while in other models each transport mode is subdivided based on vehicle sizes and driving patterns (Hagos and Ahlgren, 2020).

While there is a body of literature on energy and transport models, respectively, there is much less literature in which these models are combined. Helgesen (2013), however, discusses, in general terms, how to combine energy system models with macroeconomic general equilibrium models. He considers different degrees of linking – separate models, soft-linked models, hard-linked models, and integrated models. Gerboni et al. (2017) present a conceptual link between two families of models, energy models and transport models, illustrating the need for a connection between them. The study provides some preliminary results of integrated modelling exercises for an Italian case.

Linking with a focus on finding policy measures supporting the cost optimal technology pathways for decarbonisation of transport was done by Haasz et al. (2018). The optimization model TIMES PanEU was soft-linked to the simulation model TE3, and a model-based analysis was conducted to show possible least cost developments in the transport sector to achieve the EU goals, with a focus on emission reductions in French and German passenger car transport.

While many studies of low carbon transitions of the transport system have been directed at decarbonisation in terms of technological transformation, Pye and Daly (2015) focused on opportunities for behavioural and demand side oriented measures. Their paper explores how mode shift can contribute to low-carbon energy systems, integrating endogenous mode choice into a whole energy systems model, by representing mode speed, travel time budgets, infrastructure costs, and maximum rates of modal shift. In this work, transport demand projections for each mode remained as exogenous inputs, but authors underlined the need for the integration of transport behavioural aspects in optimisation energy models.

The IEA simulation Mobility Model (MoMo) was used to study road freight with analyses of demand side measurements specific to freight decarbonisation (Mulholland et al., 2018). A log–log multivariate linear regression model to project future national trends in road freight activity was integrated in MoMo to provide scenarios of vehicle fleet and sales, mileage, technology shares, energy demand and GHG emissions.

A review of the state of the art of the integration of energy and transport models, assessing the methodologies adopted for including aspects of behaviour in transport within integrated energy and transport models, was done by Venturini et al. (2019). They analyse 27 integrated energy and transport models and reviewed the methodologies adopted for introducing behavioural features related to consumer purchase, adoption, and use of different transport technologies. The authors conclude that there are three common approaches for structuring a model to improve the representation of behaviour: Top-down, bottom-up, and hybrid, with different pros and cons depending on the scope and purpose of analysis: Soft-linking and bottom-up structure result in the apparently most flexible and promising method. Their review identified technology and modal choice, driving patterns, and new mobility trends as key parameters for modelling transport behaviour in integrated energy and transport models.

The JRC-EU-TIMES energy model was used to evaluate the effects of the EU car CO_2 legislation up to 2050 in three scenarios (Thiel et al., 2016). For this analysis, 45 different vehicle types, including powertrains like battery electric vehicles (BEV), plug-in hybrid electric vehicle (PHEV) and hydrogen fuel cell electric vehicle (FCEV), were considered, as well as related investments and mark-up costs. In the conclusions, the authors underlined the possibility to couple optimisation models with agent-based models, to include modal shifts in the analysis. Also, an Irish study developed a multi-model approach using an energy systems optimisation model together with a car fleet simulation model to identify technology pathways, policy roadmaps and specific policy measures (Mulholland et al., 2017).

A quantitative and systematic review of the road freight decarbonisation literature done by Meyer (2020) revealed a fast-growing and interdisciplinary research field. However, no significant linkage was identified in previous work between transport and energy models.

In summary, the literature review shows relatively few studies combining energy system models with freight transport sector models. This is where our study aims to make a contribution.

3. Method

We study the total energy consumption of heavy-duty freight transport by linking several models covering Norway. These include the National Freight Transport Model (NFM), a vehicle stock-flow projection model (BIG), and a national energy system model (IFE-TIMES-Norway). First, we present the method use for interaction between the three transport models in the study, then we provide a description of the respective models.

3.1. Objectives and principles

By soft-linking models for transport demand, vehicle turnover and energy generation and use, we set out to explore how such models can complement each other and become more relevant and reliable policy support tools. An important input to both BIG and IFE-TIMES-Norway is the future demand for transport. Annual demand for freight, primarily in terms of tonne kilometres (TKM), is an output from the NFM model, coinciding with the projections of the National Transport Plan of 2022–2033 (Ministry of Transport, 2021, Madslien and Hovi, 2021). The demand projection in TKM from NFM is used to calibrate the vehicle stock-flow model BIG, which provides a detailed calculation of annual road transport activity in terms of vehicle kilometres (VKM), by powertrain

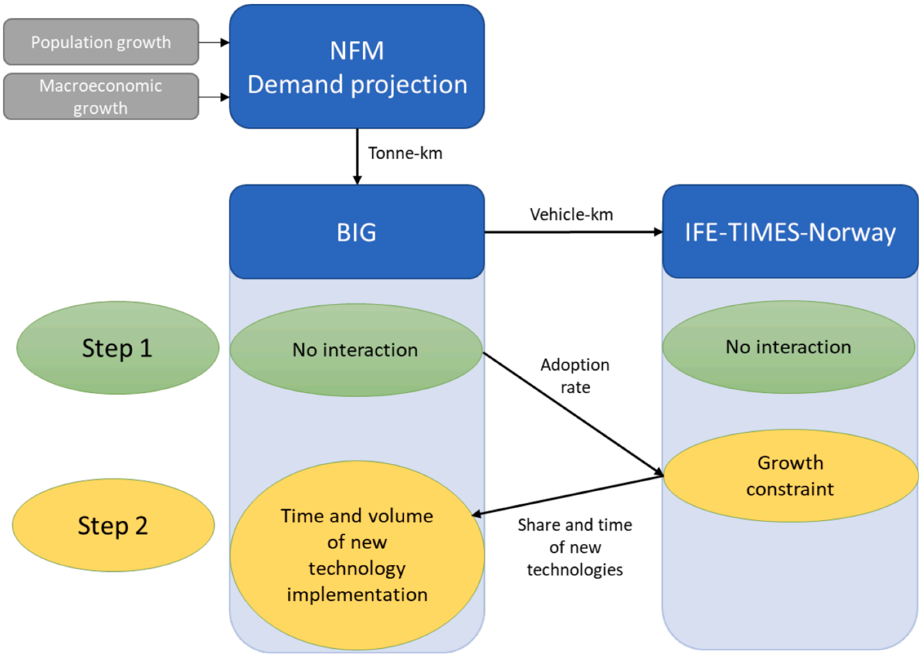

Fig. 1. Schematic overview of interaction between models.

technology, used as input to IFE-TIMES-Norway.

In the first step, IFE-TIMES-Norway runs without any restrictions on the speed of adoption of new technology in road freight vehicles. In parallel with this, the stock-flow model BIG runs with the same TKM demand projection and basic assumptions.

The introduction of a new technology in the market is typically made gradually as it gets deployed first by innovators, then early adopters, followed by the majority and finally accepted by laggards (Rogers, 1962). Moreover, since capital assets like vehicles have a service life extending over several years, or even decades, it takes time before a new technology has penetrated into the stock, no matter how superior its quality. In addition, new technology can differ in suitability and acceptance across market segments. These dynamics are relevant to consider when one models technology change in the heterogenous service of road freight.

As compared to techno-economic optimisation models, such as IFE-TIMES-Norway, a stock-flow model like BIG is more suited to depict the gradual adoption of new technologies. The former will usually presuppose a binary technology choice behaviour. The shortcoming of the BIG model, on the other hand, is the arbitrary, exogenous specification of new vehicle powertrain market shares. While IFE-TIMES-Norway can better estimate timing of introduction, BIG has the benefit of providing realistic growth rates for the various segments of the vehicle fleet.

In the second step, these strengths are combined by adding a growth constraint in IFE-TIMES-Norway. The annual in-flow of new propulsion technology in the freight vehicle fleet is calculated from the rate of adoption of zero emission technologies found in BIG at Step 1 in the linking process. The adjusted, growth constrained investment in new vehicles in IFE-TIMES-Norway is used as input to step 2 in BIG, calculating the flows of new technologies and their year-by-year impact on the stock. Fig. 1 presents a schematic overview of the interaction between models.

With this methodology TIMES will provide an economically optimal timing for phasing in the new technology considering the time needed to penetrate the stock of vehicles at a realistic pace.

3.2. Model descriptions

3.2.1. National freight model - NFM

NFM can be classified as a strategic transport network model (Jonkeren et al., 2019), consisting of the following elements:

Table 1
Overview of main input and output variables in BIG stock-flow model of the Norwegian vehicle fleet.

	Passenger cars	Rigid trucks and vans	Tractor-trailers	Buses and coaches	Campervans and motorhomes	Combined freight/ passenger vehicles
Input						
Inflow of new vehicles	X	X	X	X	X	X
Survival rates	X	X	X	X	X	X
Annual mileage	X	X	X	X	X	X
Per km energy consumption	X	X	X	X	X	X
Per km CO_2 emissions	X	X	X	X	X	X
Maximum allowed gross weight		X	X			
Capacity utilization rates		X	X			
Output						
Stock of vehicles	X	X	X	X	X	X
Outflow of vehicles	X	X	X	X	X	X
Vehicle km travelled	X	X	X	X	X	X
Energy consumed	X	X	X	X	X	X
Tonnes of CO_2 emitted	X	X	X	X	X	X
Capacity tonne km travelled		X	X			
Factual tonne km hauled		X	X			
Segmentation/classification						
# of age groups specified	31	31	31	31	31	31
# of powertrains specified	11	11	11	11	11	11
# of weight classes specified	9	9	9	4	1	1
# of cells	3069	3069	3069	1364	341	341
Key statistics						
Stock of vehicles on Dec 31, 2020	2 726 881	526 017*	9 562	16 688	58 533	12 626
Of which: BEVs, FCEVs or biogas	330 694	9 599	2	1 484	0	0

*Of which 469 757 light commercial vehicles (vans) and 56 260 heavy-duty rigid trucks.

1. Annual transport demand, represented by commodity flow matrices between suppliers (producers, importers, and wholesalers) and end-use sectors (exporters, wholesalers, retailers, and service industry), distributed over 39 commodity groups representing different requirements regarding transport quality. Commodity flows are defined between zones consisting of Norwegian municipalities, European countries, and continents overseas (Hovi, 2018).
2. A network model, representing each mode's physical infrastructure (road, sea, rail, and air) by distance and transport time, including locations of terminals for consolidation and reloading between modes (Madslien et al., 2012).
3. Cost functions representing time and distance dependent costs for different transport modes, including loading/unloading/reloading, ordering, storing, commodity time values, etc. (Grønland, 2018).
4. Optimization routines for choice of shipment size, frequency, and mode, based on a minimization of annual logistics costs (de Jong et al., 2013).

Based on transport demand for a given year and an alternating aggregate-disaggregate-aggregate methodology (Ben-Akiva and de Jong, 2013), the model determines the optimal shipment size and transport chains (number of legs, selection of modes and vehicle types) with the lowest logistics costs including optimal transfer locations for each pair of origin and destination zones.

Projections of the commodity flow matrices for future years (2030 and 2050) are based on Statistics Norway's population projections from 2020 (Leknes et al., 2018, Statistics Norway, 2020b) and macroeconomic growth trajectories compiled by the Norwegian Ministry of Finance (2020). Growth paths are regionalized using PINGO, a spatial computable general equilibrium model for Norway (Hansen, 2019). These projections apply to a situation where no new measures are being introduced to influence transport demand or mode choice.

3.2.2. Stock-flow vehicle fleet model - BIG

The BIG bottom-up stock-flow model of the Norwegian vehicle fleet distinguishes six categories of motor vehicles: passenger cars, rigid trucks and vans, semitrailer tractor units, buses/coaches, campervans/motorhomes, and combined passenger-freight vehicles. Thus, among all types of motor vehicles meant for road use, only two-wheelers are not included in the model.

Table 1 summarizes how, for each calendar year, the vehicle fleet matrix is segmented into 11 253 different cells, each cell having a number of characteristics assigned to it. Freight vehicles are described by their maximally allowed and factual gross weight (including trailer), in addition to the attributes also relevant for passenger vehicles.

As of year-end 2020, some 12 percent of the passenger cars registered in Norway were BEVs. Among vans, the BEV share was 2 percent. Among heavy-duty rigid trucks, this share was a mere 0.05 percent. Among buses and coaches, some 3 percent were BEVs, while around 6 percent were powered by biogas.

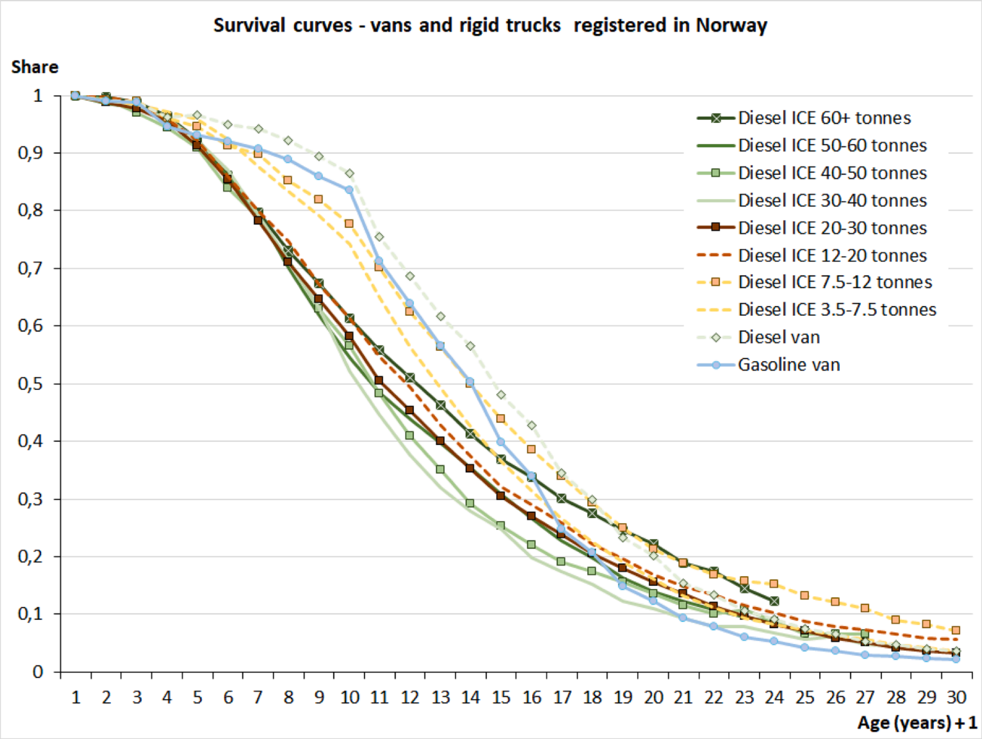

Fig. 2. Survival curves for vans and rigid trucks, by maximally allowed gross vehicle weight including trailer (metric tonnes). ().
Source: Fridstrøm, 2022

The following 11 powertrain technologies are specified:

a. gasoline ICE,
b. diesel ICE,
c. battery electric vehicle (BEV),
d. plug-in hybrid electric vehicle (PHEV) with gasoline ICE,
e. PHEV with diesel ICE,
f. non-plug-in hybrid vehicle (HEV) with gasoline ICE,
g. HEV with diesel ICE,
h. hydrogen fuel cell electric vehicle (FCEV)
i. biogas ICE
j. kerosene ICE
k. other ICE

Being based on the Markov chain principle, by which the flows and stock in year *t* depend only on the stock of the previous year/t, the model projects year-by-year changes in the fleet of vehicles in each category, classified by age, weight and powertrain technology, forming a four-dimensional matrix of 11 253 cells.

To each cell in this matrix, a set of characteristics are assigned, including year-to-year survival rates, annual mileage, energy consumption per vehicle km, maximally allowed gross weight (including trailer), average capacity utilization, as well as per km CO_2, NO_X, SO_2 and PM_{10} emission rates.

The *survival rates*, which – put simply – express what portion of the vehicles of a given age, weight group and energy technology do survive (in Norway) until next year, have been calculated on the basis of the flows and stocks observed (in the motor vehicle register) between 2012 and 2018. From these rates, survival curves and life expectancy values can be calculated, see Fig. 2 & Fig. 3. Freight vehicles in general seem to have considerably shorter lives on Norwegian license plates than do passenger cars. Many freight vehicles, especially tractor units, are sold second hand to operators in other European countries long before they are due for scrapping. Thus, the velocity of turnover is higher for heavy-duty freight vehicles than for passenger cars and vans.

Relying on this detailed empirical body of hard data, the BIG model calculates the time lag between innovations affecting the *flow* of new vehicle acquisitions and their penetration into the national vehicle *stock*.

Mileage figures for each vehicle class, weight segment, powertrain and age are based, in most cases, on the odometer readings made at periodic vehicle inspections. In some cases, data from trucking surveys are used as well. For all types of vehicles, mileage is *age*

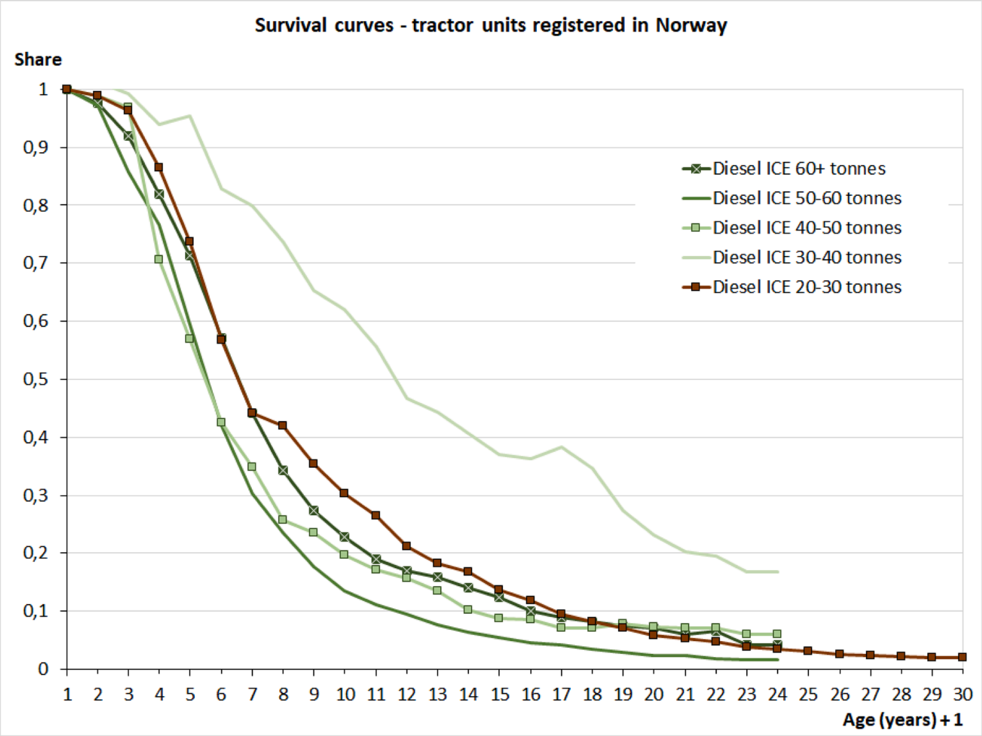

Fig. 3. Survival curves for heavy-duty tractor units, by maximally allowed gross vehicle weight including trailer (metric tonnes). ().
Source: Fridstrøm, 2022

specific, decreasing as the vehicle gets older.

Energy consumption rates are based partly on the type approval test cycle, adjusted for measurement error (Tietge et al., 2019), partly on trucking surveys and other technical specifications. Unlike mileage, energy consumption rates are *cohort specific*, i.e., they do not vary through the vehicle's lifetime, however later generations of vehicles usually exhibit somewhat lower rates than do previous ones. The same applies to the CO_2, NO_X, SO_2 and PM_{10} emission rates.

The *maximum payload* varies, of course, with the vehicle's certified gross weight. BEVs are assumed to have somewhat lower payload than diesel ICE vehicles, but the difference is small, reflecting that BEVs are allowed to weigh 1 or 2 tonnes more than similarly sized ICE freight vehicles.

The average *capacity utilization* rates are set in accordance with empirical data from trucking surveys etc. To avoid confounding effects when projections are produced, these rates are usually kept constant.

As a matter of recalibration, certain *adjustment factors* are routinely applied, so that the model reproduce, roughly speaking, the aggregate amount of road transport greenhouse gas emitted during 2015 through 2020 according to the official environmental statistics.

For a given long-term projection, the main *input* to the BIG model consists of strings of new vehicles registered every year from the base year until 2050, subdivided by vehicle class, powertrain, and gross vehicle weight. These strings are, in principle *exogenously given* and specified by the model user based on her professional insight or discretionary judgment, or in response to politically determined targets. Through interaction with the energy model IFE-TIMES-Norway, the flows of new vehicles in BIG are, however, *endogenized*. Thus, the vehicle flows and stocks become responsive to changes in technology, costs and taxation – in particular to the price of carbon, which is, at least in part, politically determined.

The *output* comprises annual vehicle stocks, vehicle kilometres driven, tonne kilometres hauled, energy consumption by powertrain or energy carrier, as well as various kinds of emissions to air.

The vehicle fleet is an inert matter. It changes slowly. It may take 8–25 years, in some cases even longer, before energy technological innovations affecting the flow of new vehicles have penetrated similarly into the stock. This energy transition time lag would tend to increase with the speed of innovation and with the target level of adoption but decrease with the velocity of vehicle turnover (Fridstrøm, 2017).

For a more complete account of the model and of its output, see Fridstrøm et al. (2020), Fridstrøm and Østli (2016) and Fridstrøm (2019).

3.2.3. Energy system model - IFE-TIMES-Norway

IFE-TIMES-Norway is a technology-rich model of the Norwegian energy system divided into five regions corresponding to the current electricity market areas. The model provides operational and investment decisions from the starting year, 2018, towards 2050, with model periods for every fifth year from 2020 to 2050. To capture operational variations in energy generation and end use, each model period is divided into 96 sub-annual time slices, where the four seasons are represented by one day of 24 h in each season.

IFE-TIMES-Norway minimizes the total discounted cost of the energy system in meeting the Norwegian demand for energy services for the period 2018–2050. The energy system cost includes investment expenditures in supply and demand technologies, storage technologies and transmission lines, operation and maintenance costs, and costs of net electricity imports.

The model has a detailed description of end-use of energy, and the demand for energy services is divided into numerous end-use categories within manufacturing, buildings, and transport. Note that energy services refer to the services provided by consuming a fuel and not the fuel consumption itself. For example, the transport demand in terms of TKM or VKM is an energy service, while the fuel used to drive the vehicle is not. Each energy service demand category can be met by existing and new technologies using different energy carriers such as electricity, biofuel, hydrogen, and fossil fuels. Other input data include fuel prices, electricity prices in countries with transmission capacity to Norway, renewable resources, and technology characteristics such as costs, efficiencies, and survival and learning curves. The discount rate used is 4 percent and the monetary unit of the model is Norwegian kroner (NOK) with an exchange rate of 1 NOK = 0.1 €.

Electricity, hydrogen, district heating and biofuels are examples of energy carriers being determined in IFE-TIMES-Norway. The prices of these energy carriers are endogenous modelling results, while petroleum products and imported biofuels are examples of energy carriers that are determined outside the model, i.e., exogenously.

The hydrogen production for the transport sector is based on electrolysis, including both proton exchange membrane (PEM) and Alkaline technology. The hydrogen can, in the model, be produced either in small-scale electrolysers located at the refuelling station, or in large scale facilities implying additional transport costs to the refuelling stations. The sizing of small-scale electrolysers has been based on hydrogen demand identified in main Norwegian transport corridors in 2030 (Danebergs et al., 2021a).

In IFE-TIMES-Norway, the vehicles are divided into six different segments: passenger cars, vans (LCVs), medium trucks (less than50 tonnes GVW including trailer), large trucks (greater than50 tonnes GVW) for short haul driving (less than300 km/day), large trucks (greater than50 tonnes GVW) for long-haul driving (greater than300 km/day), and buses/coaches.

The three truck types provide the division of vehicles in approximately-three equally large groups in terms of total annual fleet mileage. The average weight of Norwegian registered trucks is relatively high by European standards, as the maximally allowed GVW on the Norwegian road network is 50 tonnes, and for selected road stretches up to 60 tonnes. Vans are defined as commercial vehicles with GVW less than 3.5 tonnes excluding trailer.

These demand segments correspond to differing technological requirements. As a restriction it is assumed that all demand segments may be served by battery electric vehicles, except for trucks heavier than 50 tonnes GVW and traveling more than 300 km/day. This constraint is introduced due to the challenges to integrated battery size and/or recharging speeds, however with the fast technological development this assumption might need to be reassessed.

The segmentation/classification of freight vehicles in IFE-TIMES-Norway is not at all as detailed as in BIG, but the two models are compatible at a more aggregate level.

Besides road transport, the model covers the modes of rail, sea, and air. In addition, a category gathering the rest of transport demand is included in “other transport”. The transport demand can be satisfied by various technologies or powertrains. The powertrains included in IFE-TIMES-Norway are ICE, plug-in hybrid with ICE, battery electric, fuel cell electric and biogas powered ICE. More detailed descriptions of IFE-TIMES-Norway and of the TIMES tool are presented in (Danebergs et al., 2021b) and in (IEA-ETSAP, 2022), respectively.

All the electric vehicles depend on access to charging infrastructure, which brings an additional cost to the system in comparison with current well-established petrol station infrastructure (included in the diesel prices). As BEVs are assumed to require frequent charging, the charging profiles are based on almost 50 000 recorded events of trucks stopping for a longer period of time (Hovi et al., 2021). The fast-charging profiles are selected based on a 30–90-minute break that vehicles are making after being driven for more than 3.5 h. It is chosen based on the mandatory 45 min break truck drivers are required to take after max 4.5 h driving, thus a natural moment to top up the battery within a working shift. Slow charging is assumed to begin when vehicle is standing still for at least 90 min after the same 3.5 h driving threshold. The slow charging profile is refined by assuming a charging time for 8 h once stopped and by that smoothing out the charging profile. Both profiles are shown in Fig. 4. Trucks with GVW below 50 tonnes are assumed to mainly be used for distribution of goods and that only 25 percent of their energy demand is delivered by fast chargers. This is based on the assumption that two thirds of daily mileage, for vehicles with engine power below 500 horsepower (~370 kW) and not older than 5 years, is below 200 km (Hovi et al., 2019). For large trucks with daily mileage below 300 km only slow charging is assumed, as such daily mileages are assumed possible to cover with a battery that has been recharged overnight.

4. Empirical illustration of linking

The NFM, BIG and IFE-TIMES-Norway models differ in terms of scope, structure, classifications, behavioral relations, and levels of aggregation. To soft-link the models, one needs to build certain bridges between the concepts, variables and definitions used. The challenges and solutions involved in this process are best explained by way of an empirical illustration.

4.1. An ambitious greenhouse gas abatement scenario

We start from the assumption that to achieve the greenhouse gas (GHG) emissions targets, fairly high rates of technology learning and carbon pricing will be called for. The linking methodology presented in this paper uses a scenario that presupposes the enactment of sharpened EU regulations on new vehicles and a CO_2 tax on fuel increasing to NOK 10 000 per tonne CO_2 in 2040. All other taxes, including the NOK 3.56 per litre ‘road use tax’ on diesel, are kept constant at the 2020 level. In our modelling exercise, the targets formulated in EU regulations 2019/631 and 2019/1242 are translated into assumptions that no less than 15 percent of new heavy-duty vehicles will be zero emission vehicles (ZEVs) in 2025, rising to at least 30 percent in 2030. For new vans, a floor of no less than 45 percent ZEVs is assumed for 2025. More scenarios and sensitivities have been analysed and more details are presented by Danebergs et al. (2021a) and Fridstrøm and Østli (2021).

The demand projection from NFM is a driver in both BIG and IFE-TIMES-Norway. Table 2 presents indices for the calculated development of freight transport demand. Transport volumes in terms of TKM calculated in NFM are translated into VKM split between several categories of vehicles in BIG. These data are recalculated to conform with the categories of IFE-TIMES-Norway and divided into the five electricity market areas based on data from NFM at county level (19 counties).

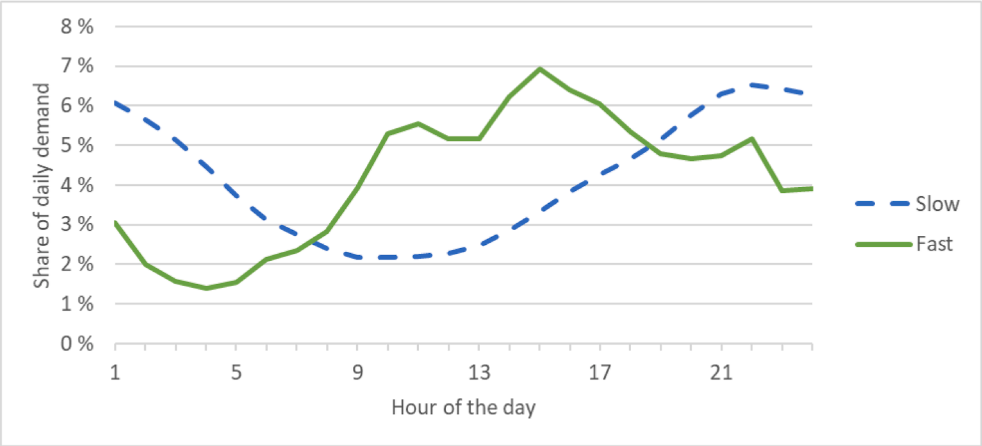

Fig. 4. Aggregated slow and fast charging profiles as hourly share of daily energy demand, based on start and stop driving patterns gathered from Norwegian trucks (Hovi et al., 2021) and a smoothing out of slow charging profile.

Table 2
Indices for transport demand (TKM) in 2030 and 2050, set to 100 in 2018 (Madslien and Hovi, 2021).

		Demand index (TKM)		
		2018	2030	2050
Road freight	Total	100	132	169
	Medium trucks	100	79	72
	Large trucks	100	132	186
Sea freight		100	116	130
Rail freight		100	121	144

There is a shift from smaller to larger trucks and tractor-trailers, in line with recent trends (Fig. 5). The trends in urban logistics of rising e-commerce, next-day deliveries and growing craftsman and mobile service industries, driving a fast growth rate for smaller freight vehicles, is reflected in the BIG model through the rapidly increasing inflow of new light commercial vehicles (vans), which massively outnumber the heavy-duty freight vehicles (Fig. 6).

4.2. *Quantitative assumptions*

The review of technological and economic data has been an important part of our study. Particularly important sources are studies by UC Davies (Fulton et al., 2019), TØI (Figenbaum et al., 2019, Pinchasik et al., 2021) and the "Klimakur 2030" report (Norwegian Environment Agency, 2020). Table 3 presents important technology parameters.

The limitations, set in the model, for biofuels and biogas are of high importance for the transport sector results. Domestic wood-based biomass is a limited resource, not exceeding 31 TWh/year, which is used by multiple sectors within the country as well as traded in the international market (Danebergs et al., 2021b). The IFE-TIMES-Norway model includes use of biomass as chips/pellets in heating plants, conversion to biofuel or conversion to charcoal, in addition to use as raw material in manufacturing industry. An important limitation in the model is zero import of biofuels or charcoal from 2035 based on the assumption that Norway as a country, relatively rich in biomass resources, should be self-sufficient in a sustainable energy system.

Biogas is also a limited resource, calculated at 0.4 TWh in the start year increasing to 1.2 TWh/year in 2035, at a cost of 1 NOK/kWh, and in addition 1.5 TWh/year at a cost of 2 NOK/kWh (Carbon Limits, 2019). It is possible to blend biofuels with fossil fuel for use in ICE. In 2020, the minimum mandatory blend-in is 15.5 percent, while the upper limit increases linearly to 100 percent by year 2040. Biogas is possible to use in dedicated combustion engines adapted for gaseous fuel. The cost of fossil diesel and imported biodiesel is set exogenously at 1.031 NOK/kWh and 1.641 NOK/kWh, respectively (Carbon Limits, 2019, Norwegian Environment Agency, 2020).

Even if the electricity prices are calculated endogenously in the model, they are impacted heavily by electricity prices for countries with transmission capacity to/from Norway. These are set for the base year as the average prices from 2018, from NordPool (2020) and ENTSO-E (2020) while the future prices are based on the long-term estimations by NVE (2021).

Obviously, our empirical illustration, developed during 2020–2021, does not take into account the violent price variations affecting

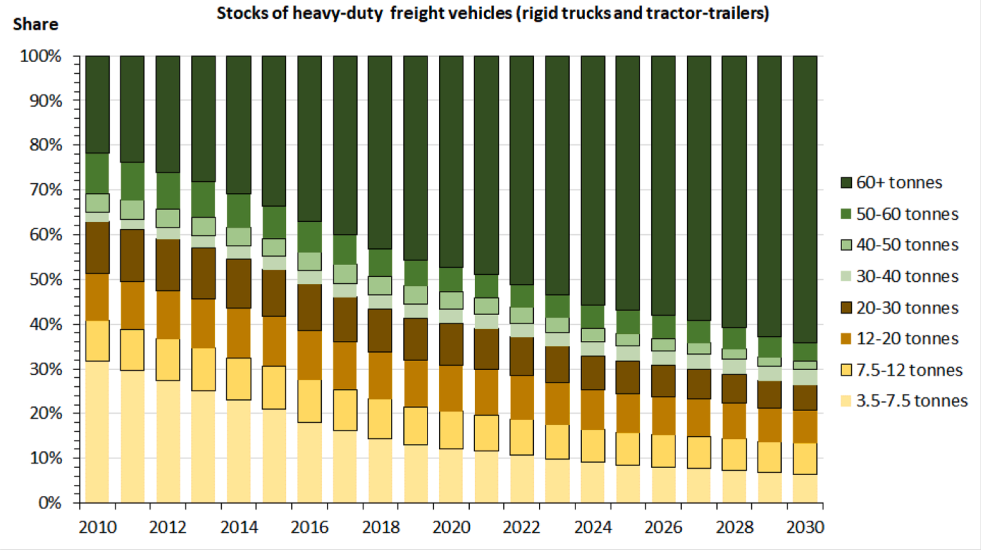

Fig. 5. Stocks of rigid trucks and tractor-trailers, by maximally allowed gross vehicle weight. Observed stocks 2010–2020 and projected stocks 2021–2030.

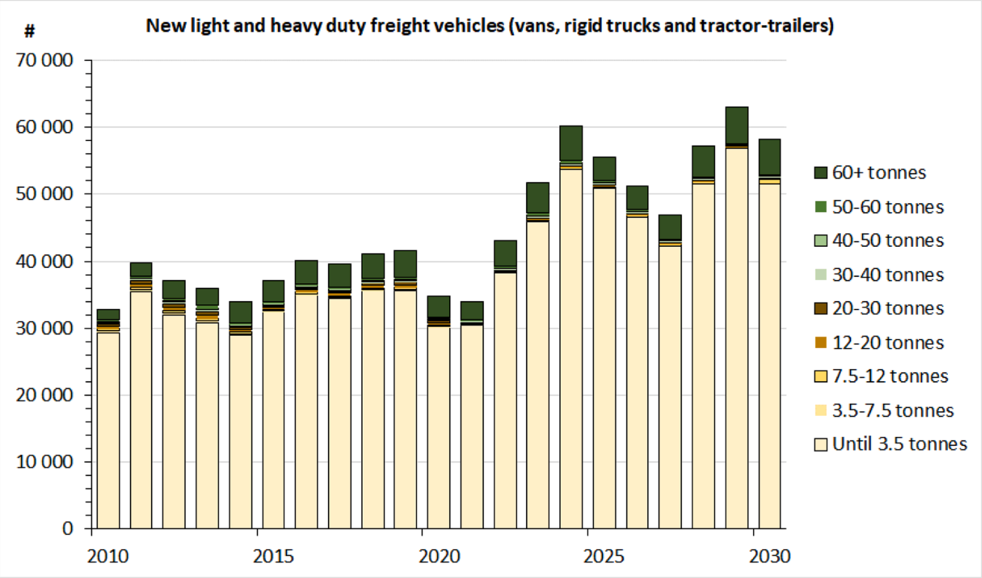

Fig. 6. New light and heavy-duty freight vehicles, by maximally allowed gross vehicle weight. Observed annual flows 2010–2020 and projected flows 2021–2030.

Table 3
Vehicle parameters in IFE-TIMES-Norway (1 NOK = 0.1 €).

	Lifetime	Average annual mileage	Investment cost			Energy efficiency	
			2018	2030	2050	2018	2050
Unit	Years	km	kNOK/ vehicle			kWh/km	
Vans	15	15 300					
ICE			230	236	236	0.7	0.62
BEV			506	248	248	0.23	0.21
Plug-in			308	281	281	0.41	0.36
Fuel Cell			770	362	362	0.34	0.29
Trucks, small	15	30 000					
ICE			1500	1500	1500	3.4	3.1
Gas			1700	1700	1700	4.2	3.8
BEV			4250	2910	1515	1.5	1.5
Fuel Cell			5800	3444	1710	2.5	2.5
Trucks, large, short haul	13	35 000					
ICE			1500	1500	1500	4.8	4.4
Gas			1700	1700	1700	5.9	5.5
BEV			4400	3104	1515	2.1	2.1
Fuel Cell			5800	3658	1710	3.6	3.6
Trucks, large, long haul	6	90 000					
ICE			1500	1500	1500	4.2	3.9
Gas			1860	1860	1860	5.3	4.8
Fuel Cell			5800	3658	1710	3.1	3.1
Source	(Statistics Norway, 2019, Danebergs et al., 2021b)		(Figenbaum et al., 2019, Danebergs et al., 2021b, Fulton et al., 2019, Norwegian Environment Agency, 2020, Pinchasik et al., 2021)			(Islam et al., 2018, Fulton et al., 2019, Hovi et al., 2021)	*

*Assumed constant annual improvement of 0.37 percent for vans and 0.26 percent for trucks from 2018 to 2050.

energy markets since February 2022.

4.3. Linking results

4.3.1. Market uptake and penetration of zero emission vehicle technology

In the BIG model, the *flows* of new vehicles are exogenous. The model user is required to specify, for each year, the number of new units within each vehicle category, weight class and powertrain technology segment. The BIG model then calculates the *stock* of vehicles, likewise classified and segmented, onto the 2050 horizon. In most applications so far, the specification of new vehicle flows has been based on trend extrapolation or on some politically defined targets for the market uptake of zero and low emission technology.

The IFE-TIMES-Norway model offers, however, an opportunity to endogenize the flows of new vehicles. Based on assumptions regarding energy prices, technology development and fiscal and regulatory incentives, IFE-TIMES-Norway calculates, for each time period, an optimal mix of technology within each vehicle category.

Changes in optimal technology does not, however, immediately translate into changes to the vehicle stock. The rolling stock consisting of durable assets, it takes time before new technologies penetrate the fleet. We use this time lag, calculated by the BIG model, to roughly specify certain growth constraints in the IFE-TIMES-Norway model. The growth constraints limit the speed at which technology changes can occur, capturing the inertia of vehicle fleets.

An illustration is given in Fig. 7. The annual growth rates implemented in IFE-TIMES-Norway, based on a first run on the BIG model (‘step 1′), were 21 percent for zero emission vans and 17 percent for zero emission trucks.

The various propulsion technologies are represented in different degrees among new vans and trucks, respectively, in step 1 of the stock-flow model, as shown in the left part of Fig. 8. In a second step, we rerun the IFE-TIMES-Norway model based on the derived growth constraints (‘step 2′) and use the output as input to BIG. The share in BIG is changed as shown in the right part of the figure. The transition to 100 percent battery electric new vans is hurried up and occurs in 2030 instead of in 2050, as originally assumed in BIG.

The transition to zero emission trucks occurs faster when, in step 2, the energy system model is used to optimize powertrain technology investments. Full electrification, by batteries or fuel cells, of new heavy-duty freight vehicles is seen to occur in 2040 instead of after 2050. In the medium term, i.e. until 2030, biogas technology is projected to play an important role. FCEVs are projected to become economically attractive after 2035.

4.3.2. Effect of linking on model results

The projected stocks of vans and trucks, segmented by powertrain technology, are presented in Fig. 9. When, in step 2, we apply a constraint to the speed of adoption of new vehicle technology, transition to ZEVs is delayed in the energy system model, and the use of ICE vehicles lingers longer into the future. The opposite is noted for the stock-flow model, where ZEVs are introduced at a higher speed than originally.

The linking also increases the use of PHEVs and biogas vehicles in the intermediate period, because of delayed adoption of BEVs and FCEVs in the energy system model.

With the exchange of information between the two models, the projected stocks of vehicles with differing powertrains become much more similar after a couple of iterations than at the outset. But some differences inevitably remain. One important reason is that the two models rely on different classifications and levels of aggregation. IFE-TIMES-Norway models the vehicle stock in a less detailed fashion than BIG and thus does not keep track of the heterogeneity of the vehicle fleet. BIG, on the other hand, does not assign vehicles to short or long-distance haulage. Certain ad hoc ‘translations’ have been made between the models in order to ensure consistency at a more or less aggregate level.

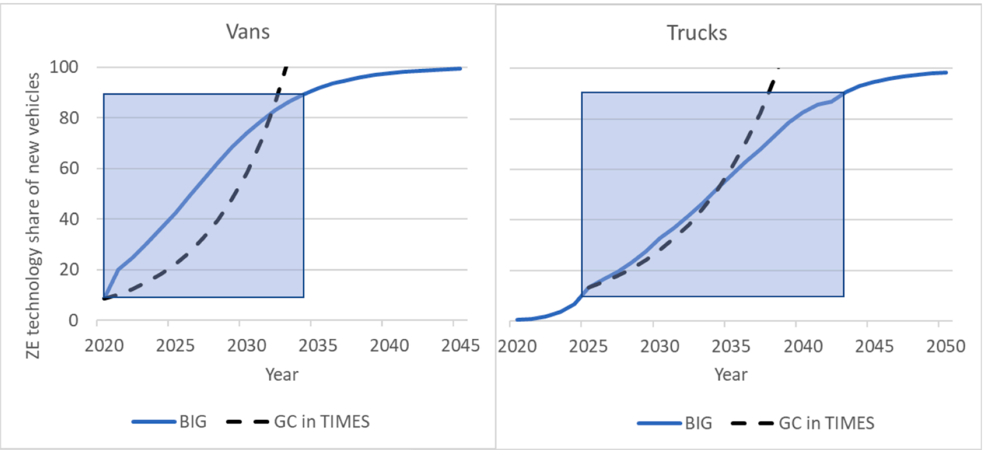

Fig. 7. Share of new zero emission vans and trucks in BIG and the corresponding growth constraint (GC) implemented in IFE-TIMES-Norway.

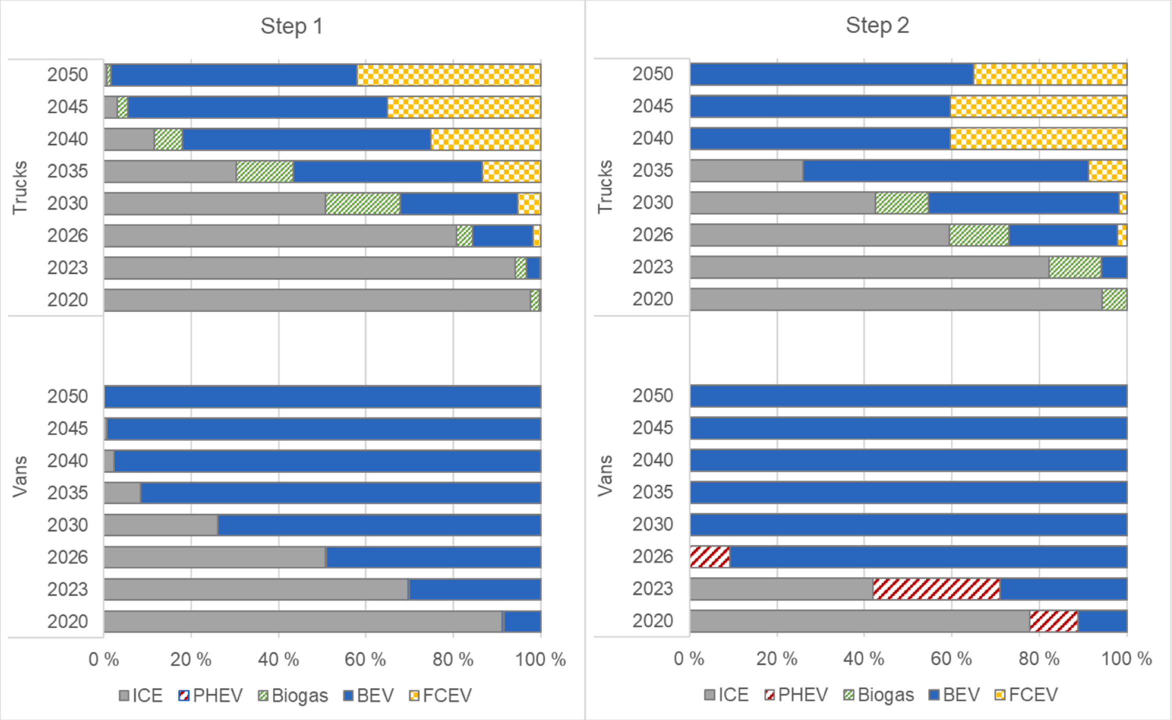

Fig. 8. Shares of different propulsion technologies of new trucks and vans used as input to the stock-flow model BIG. Step 1(left) and step 2 (right).

4.3.3. *Energy use and impact on energy system*

The end-use demand for energy, by carrier, is an output from IFE-TIMES-Norway. As can be seen in Fig. 10, the projected energy use changes when account is taken of the inertia calculated by BIG, particularly in the medium term. In 2030, the use of diesel increases from 6.4 TWh to 9.9 TWh from step 1 to step 2 in the IFE-TIMES-Norway analyses. Another impact is the earlier implementation of FCEVs on a small scale from 2026, calculated in step 2, while in step 1 there was hardly any use of hydrogen until 2035. From 2045 onward, results in both steps coincide.

In Fig. 11, we compare the energy use projected by the two models. The difference is small as of 2050, but bigger in 2030. But even for this year consistency is much improved through our brief loop of iteration between the two models. Due to the input from BIG, IFE-TIMES-Norway has a much slower adoption of BEVs in step 2. The use of diesel is lower than in BIG, because of the less detailed modelling of vehicles in IFE-TIMES-Norway, which does not take fully into account the life expectancy characterizing the various vehicle segments, leading to a faster phase-out of diesel technology than what follows from the BIG model.

The aggregate energy consumption of vans and trucks is projected to decrease, due to improved energy efficiency of new vehicles, particularly BEVs. The demands for electricity and hydrogen will, however, increase. The annual electricity demand in BEVs grows from the present level of 1 TWh to 15 TWh in 2050 (including passenger cars). The total use of electricity in all transport modes is projected to increase to 19 TWh. This result is well in line with other analyses of transport energy demand in Norway (NVE, 2021, Statnett, 2020, DNV, 2021). In addition, electricity for ‘green’ hydrogen used for road transport is increased to 6 TWh in 2050, giving in total 21 TWh electricity used for road transport in 2050.

The linking of the models has no impact on the projected Norwegian power production or the electricity and hydrogen prices. IFE-TIMES-Norway calculates endogenously the electricity and hydrogen prices for use in road transport. The marginal electricity prices for BEVs varies in average between 1.2 and 1.6 NOK/kWh in 2050 and the hydrogen price is calculated to about 1.7 NOK/kWh in 2050.

The linking of the energy system model and the stock-flow model gives a slower decrease in the CO_2 emissions from freight transport in the period 2023–2040 due to slower adoption of ZEVs, see Fig. 12. In a longer perspective, the linking has no impact on the emissions.

5. Discussion

By soft-linking models for transport demand, vehicle turnover and the energy system, we investigate if the models can complement each other and thus become more relevant as policy support tools. In the case of Norway, we have analysed the country’s climate targets with emissions cuts of 80 to 95 percent by 2050 compared with 1990, and how the transport sector can contribute to reach this target. This paper is mainly methodological; thus, we have not made a thorough assessment regarding the realism of the Norwegian climate targets.

As discussed by Haasz et al. (2018) the transport sector is of great importance if the target of becoming a low-carbon economy by

Fig. 9. Projected shares of stocks of light and heavy-duty freight vehicles, by powertrain technology, in steps 1 and 2 of IFE-TIMES-Norway and BIG.

2050 is to be reached, as the transport sector is a large consumer of final energy, with high emissions of GHG. Important measures emphasized in their analysis are improved fuel efficiency, less carbon intensive energy carriers, and better utilization of transport networks.

According to our analysis, the improved efficiency and reduced emissions by substitution from ICE to BEV and FCEV are important, not only to reduce energy demand, but also to reduce emissions. Development in the rate of utilization for freight vehicles is addressed

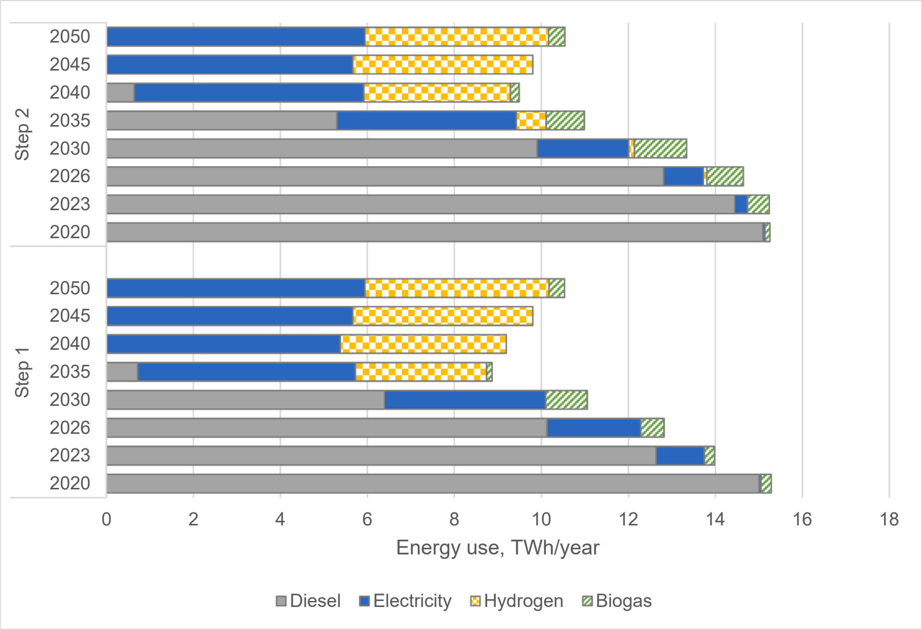

Fig. 10. Projected energy use by heavy-duty freight vehicles in steps 1 and 2 of IFE-TIMES-Norway.

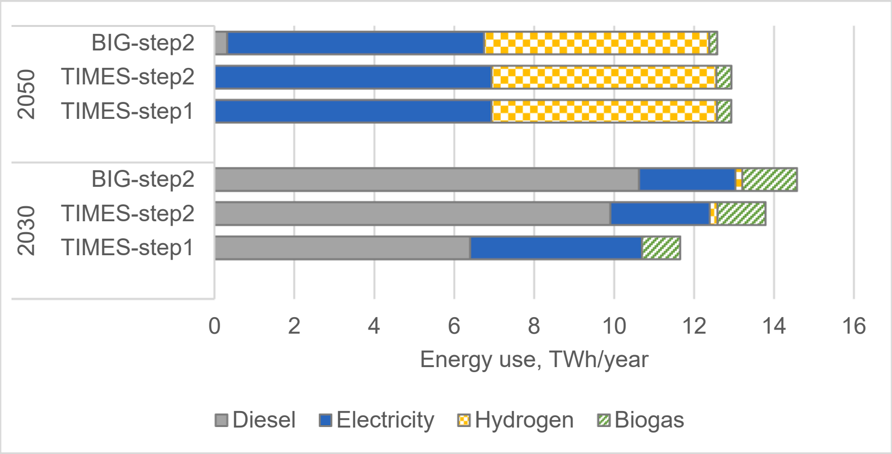

Fig. 11. Projected energy use by vans and trucks in 2030 and 2050. Step 1 and 2 of IFE-TIMES-Norway and step 2 of BIG. Energy loss by electrolysis and battery recharging is included.

by the NFM and is included in projections for future demand for transport which is used as input to the vehicle stock-flow model and the energy system model.

With respect to the modelling results, the main finding in our analysis is that for trucks up to 50 tonnes GVW and the large trucks operating less than 300 km/day, the BEV becomes the dominant technology due to the efficiency, maturity, and cost advantage over FCEVs. The FCEV powertrain is, in our modelling framework, chosen only for large trucks which run greater than 300 km/day, under the assumption that this segment cannot be served by BEVs. Previous studies have both backed up and contradicted such an assumption, while it is hard to draw conclusions at this stage of development. A scenario where BEVs can serve also the large, long haulage truck segment would give a similar result, probably with a bit faster transition towards zero emission, as BEVs have lower investment and operational costs than FCEVs. Also, energy consumption would come down, since BEVs are far more energy efficient than FCEVs.

For FCEVs to be able to compete directly with BEVs, there is a need for fast technology development, financial support for hydrogen infrastructure, and, more generally, a battery of incentives that may not be compatible with the paradigm of technology neutrality. Hydrogen production has increasing returns to scale, which more probably will be reached faster in other sectors than road freight, where FCEVs meet fierce competition from BEVs. To unlock the economies of scale in hydrogen production, the test ground and future

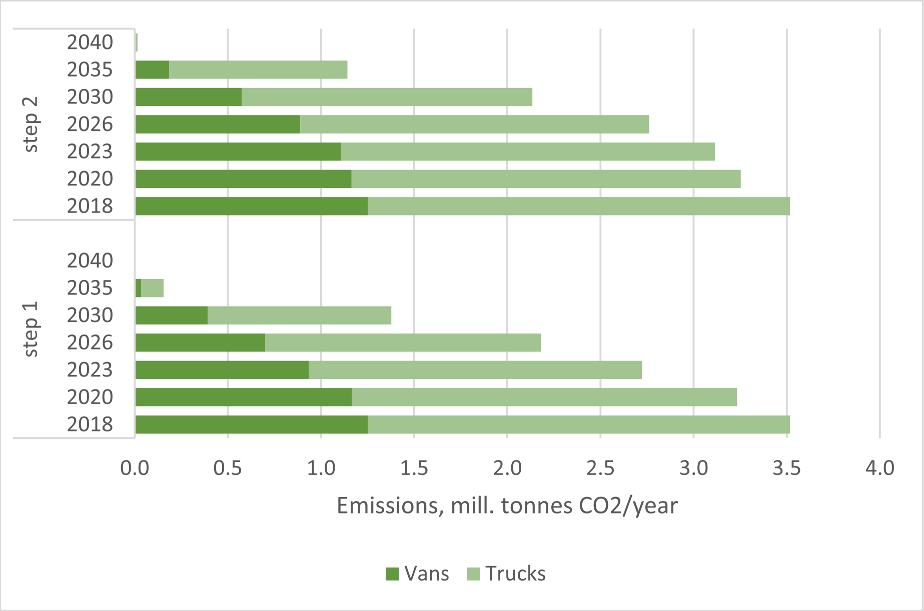

Fig. 12. Projected CO_2 emissions from road freight 2018–2040, according to steps 1 and 2 of the energy system model.

roll-out of FCEVs should be seen in connection with green and blue hydrogen production for other purposes, such as in ports or manufacturing clusters. Further research on how hydrogen technologies can be adopted and give rise to synergies in transport and manufacturing is needed.

Decarbonization of transportation may also be achieved by use of biofuels, incl. biogas. In our approach, we have assumed that Norway must be self-sufficient in bio energy in the future. But domestic biomass resources are not sufficient to play a central role in the decarbonization of the road transport sector in the long run, considering that biomass is demanded in the manufacturing and housing sectors as well. However, biofuels will play an important role in reducing GHG emissions from the transport sector until 2035.

According to the energy system model, the emissions from commercial vehicles by 2030 decrease by 61 percent at step 1, while when linked to the stock-flow model the cut is reduced to 39 percent. It highlights the importance of including more parameters, such as adoption rate of new technology, in an optimisation model like IFE-TIMES-Norway. This also emphasizes the great challenge to significantly reduce the emissions within a limited timeframe.

The modelling results show that continued technology development in battery and hydrogen technologies are important in order to achieve Norway's national climate targets. This is in line with previous studies, stating that for battery electric trucks, the cost, energy density and lifetime of batteries are constraints and need improvement (Cano et al., 2018). For FCEVs, the cost of fuel cells and hydrogen prices are important barriers in the competition with ICEs (Zhao et al., 2018).

Other societal barriers such as charging or waiting time, driver inconvenience, or resistance to change have not been considered in this analysis in detail, except in the form of a general adoption rate. We have assumed that the drivers adapt to the technology. We need more research on barriers and social aspects of the implementation of zero emission trucks to understand if the drivers adapt to the vehicle technology, or if the vehicle technology must adapt to the drivers' habits, routines and regulatory constraints.

The methodology described illustrates the advantages of using a multi-model approach for analyses of decarbonization of road freight transport, as stated, in the introduction, as our first research question. In a stand-alone run, the stock-flow model has exogenously given strings of new vehicles. Through interaction with the energy system model, the flows of new vehicles are endogenized in the stock-flow model. The energy system model is improved with growth constraints making the pathway and time frame more realistic. By implementing the adoption rate of zero emission vehicles from the stock-flow model in the energy system model, we find that decarbonisation slows down in the medium term, highlighting the importance of strong fiscal and regulatory policies and incentives. This answers our second research question on the impacts of zero emission commercial vehicles on the energy system and on future CO_2 emissions.

6. Conclusions

The idea of this study has been to combine sector models for energy and transport and to model the interaction between the energy system and the freight transport sector. We have demonstrated how the combination of three different models, a national freight model, a stock-flow vehicle fleet model and an energy system model, can provide more relevant and reliable results. We have used this modelling framework to analyse the impacts on the energy system of a transition towards a zero-emission commercial road freight industry. Like the recommendations in Venturini et al. (2019), our approach is based on a soft-linking of the vehicle stock flow model and the energy system model, as well as a bottom-up structure, resulting in a flexible and feasible model integration. This linking approach is tested on an ‘optimistic’ decarbonisation scenario regarding future technology development, energy and carbon prices, emissions regulations etc. The linking enhances the policy support potential of the stock-flow vehicle fleet model and the energy system model.

The vehicle stock-flow model itself provides little information concerning the introduction of new propulsion technologies, as there is no empirical experience to draw on for heavy-duty freight vehicles. Through linking to the energy system model, the stock-flow model was improved by new input on the availability of new vehicle technologies. The energy system model was improved by implementing time lags for the penetration of new powertrain technologies derived from the stock-flow model. These time lags are translated into constraints on the pace of adoption of new technologies and can be regarded as a way of including behaviour and barriers in the energy system model. A common limitation of optimisation models is the lack of behavioural realism, which we remedy by linkage to a vehicle stock-flow simulation model.

The demonstrated method of linking models is applicable to other technologies as well as in other geographical regions, since the method is not limited to our empirical case of Norwegian freight transport. The method may be useful when new technologies are introduced to the market, while little or no empirical data are available. Typically, simple stock-flow models with exogenously specified market uptake of new technology may not give very reliable predictions. Such models can be greatly enhanced through relationships that explain technological innovation. Energy system optimisation models, on the other hand, tend to disregard or underplay the time needed for a new equilibrium to be reached. These tools can be enhanced with the help of a stock-flow model for the most significant durable assets, allowing for a more realistic pace of penetration of new technologies.

Our study shows that electrification of road freight has limited impact on the energy system, including low peak demand, at the aggregate level. Previous studies have shown potential for extensive slow charging of battery trucks. Studies of technology development indicate the possibility for high learning rates of new trucks. Together these circumstances suggest that on a system level, decarbonisation of road freight is feasible. Our work contributes with insights about the initiatives and time frames needed for the transition.

Due to the implementation of limited growth rate in the energy system model, the model result shows a decrease in carbon emissions from commercial transport in the period 2023–2040, with an emissions reduction of 39 percent between 2018 and 2030, in lieu of the 61 percent cut projected by the energy model system alone. This reduction was achieved in a highly ambitious scenario with carbon tax on fossil fuel reaching 5 000 NOK/tonnes CO_2 in 2030 and 10 000 NOK/tonnes CO_2 in 2040. It highlights that with an ambitious climate policy, significant emissions reduction from the Norwegian road freight can be achieved by 2030. To accelerate the decarbonisation within this transport segment, a sector specific stick and carrot policy might be required to increase the adoption rate of zero emission technologies.

CRediT authorship contribution statement

Eva Rosenberg: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization. **Kari Espegren ::** Project administration, Validation, Writing – review & editing. **Janis Danebergs:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – review & editing. **Lasse Fridstrøm:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – review & editing. **Inger Beate Hovi:** Formal analysis, Resources, Writing – review & editing. **Anne Madslien:** Formal analysis, Resources, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Basma, H., Saboori, A. & Rodríguez, F. 2021. Total cost of ownership for tractor-trailers in Europe: Battery electric versus diesel. International Council on Clean Transportation. https://theicct.

Ben-Akiva, M. & De Jong, G. 2013. The aggregate-disaggregate-aggregate (ADA) freight model system. *Freight transport modelling.* Emerald Group Publishing Limited.

Brown, T., Schlachtberger, D., Kies, A., Schramm, S., Greiner, M., 2018. Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system. Energy 160, 720–739.

BYD. *Press Release: BYD Is Leading The Transition To A Zero-Emissions Future With Advanced Battery Electric Trucks, Buses And Forklifts - BYD USA* [Online].2021. Available: https://en.byd.com/news/press-release-byd-is-leading-the-transition-to-a-zero-emissions-future-with-advanced-battery-electric-trucks-buses-and-forklifts.

Cano, Z.P., Banham, D., Ye, S., Hintennach, A., Lu, J., Fowler, M., Chen, Z., 2018. Batteries and fuel cells for emerging electric vehicle markets. Nature Energy 3, 279–289.

Capros, P., Zazias, G., Evangelopoulou, S., Kannavou, M., Fotiou, T., Siskos, P., De Vita, A., Sakellaris, K., 2019. Energy-system modelling of the EU strategy towards climate-neutrality. Energy Policy 134, 110960.

Cunanan, C., Tran, M.-K., Lee, Y., Kwok, S., Leung, V., Fowler, M., 2021. A Review of Heavy-Duty Vehicle Powertrain Technologies: Diesel Engine Vehicles, Battery Electric Vehicles, and Hydrogen Fuel Cell Electric Vehicles. Clean Technologies 3, 474–489.

Daimler. *Innovative solutions for the energy transition in road freight transport* [Online].2021. Available: https://www.daimler.com/company/news/daimler-trucks-now-and-next-2021.html .

Danebergs, J., Rosenberg, E. & Espegren, K. A. 2021a. Impact of zero emission heavy-duty transport on the energy system. Report *IFE/E*-2021/002.

Danebergs, J., Rosenberg, E., Seljom, P. M. S., Kvalbein, L. & Haaskjold, K. 2021b. Documentation of IFE-TIMES-Norway v2. Report *IFE/E*-2021/005.

De Jong, G., Ben-Akiva, M., Baak, J. & Grønland, S. 2013. Method report - Logistics model in the Norwegian National Freight Model System (version 3).

DNV 2021. Energy Transition Norway 2021.

Emoss, *Emoss: Zero-emission power systems for heavy equipment* [Online].2021. Available: https://www.emoss.nl/en.

Enova. *Land transport - Industry with environmentally friendly potential (In Norwegian: Landtransport – Næring med miljøvennlig potensial)* [Online].2021. Available: https://www.enova.no/bedrift/landtransport.

Entso-E. *ENTSO-E Transparency Platform* [Online].2020. Available: https://m-transparency.entsoe.eu.

Esoro. *Heavy-duty fuel cell truck* [Online].2022. Available: https://fuelcelltrucks.eu/project/esoro/.

European Council. *Climate change: what the EU is doing* [Online].2021a. Available: https://www.consilium.europa.eu/en/policies/climate-change.

European Council. *Fit for 55* [Online].2021b. Available: https://www.consilium.europa.eu/en/policies/green-deal/eu-plan-for-a-green-transition/#.

Figenbaum, E., Ydersbond, I. M., Amundsen, A. H., Pinchasik, D. R., Thorne, R. J., Fridstrøm, L. & Kolbenstvedt, M. 2019. 360 degree analysis of the potential for zero-emission vehicles (*In Norwegian: 360 graders analyse av potensialet for nullutslippskjøretøy*). TØI report 1744/2019.

Fridstrøm, L., 2017. From innovation to penetration: Calculating the energy transition time lag for motor vehicles. Energy Policy 108, 487–502.

Fridstrøm, L., 2021. The Norwegian vehicle electrification policy and its implicit price of carbon. Sustainability 13, 1346.

Fridstrøm, L., 2022. Motor vehicle demographics. Kjøretøyenes demografi), (In Norwegian. TØI report 1888/2022.

Fridstrøm, L. & Østli, V. 2016. Vehicle fleet forecasts based on stock-flow modeling *(In Norwegian: Kjøretøyparkens utvikling og klimagassutslipp. Framskrivinger med modellen BIG)*. TØI report 1518/2016.

Fridstrøm, L., Hovi, I. B., Kristensen, N. B., Madslien, A., Bruvoll, A., Gulbrandsen, M., Seeberg, A. & Aalen, P. 2020. Transport modelling for climate policy support *(In Norwegian: Transportmodeller for klimaanalyse)*. TØI report 1769/2022.

Fridstrøm, L., Espegren, K. A., Danebergs, J., Hovi, I. B., Madslien, A. & Rosenberg, E. 2022. A pathway to zero emission road freight *(In Norwegian: Veikart for utslippsfri veitransport)*. TØI report 1880/2022.

Fridstrøm, L., Østli, V., 2021. Slow, fast or extra fast. Exploring decarbonization pathways for road transportation in Norway *(In Norwegian: Forsering eller hvileskjær? Om utsiktene til klimagasskutt i veitransporten)*. Institute of Transport Economics, Oslo. TØI report 1846/2021.

Fridstrøm, L. 2019. Electrifying the Vehicle Fleet: Projections for Norway 2018-2050 *(In Norwegian: Framskriving av kjøretøyparken i samsvar med nasjonalbudsjettet 2019)*. TØI report 1689/2019.

Fulton, L., Miller, M., Burke, A., Wang, Q. & Yang, C. 2019. Technology and Fuel Transition Scenarios to Low Greenhouse Gas Futures for Cars and Trucks in California.

Gea-Bermúdez, J., Jensen, I.G., Münster, M., Koivisto, M., Kirkerud, J.G., Chen, Y.-K., Ravn, H., 2021. The role of sector coupling in the green transition: A least-cost energy system development in Northern-central Europe towards 2050. Applied Energy 289, 116685.

Gerboni, R., Grosso, D., Carpignano, A., Dalla Chiara, B., 2017. Linking energy and transport models to support policy making. Energy Policy 111, 336–345.

Gray, N., Mcdonagh, S., O'shea, R., Smyth, B., Murphy, J.D., 2021. Decarbonising ships, planes and trucks: an analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors. *Advances.* Applied Energy.

Grønland, S. 2018. Cost models for transport and logistics - base year 2016 *(In Norwegian: Kostnadsmodeller for transport og logistikk–basisår 2016)*. Report 1638/2018.

Grønt Landtransportprogram. *Charging infrastructure for heavy transport and machinery. What is happening and what needs to be done? (In Norwegian: Ladeinfrastruktur for tungtransport og maskiner. Hva skjer, og hva må gjøres?)* .2021. Available: https://www.youtube.com/watch?v=eYZHOqf4S3o&ab_channel=AmundKvernvold.

H2 Truck. *H2 Truck,* [Online].2021. Jan Carsten Gjerløw. Available: https://www.h2truck.no/om .

Haasz, T., Gómez Vilchez, J.J., Kunze, R., Deane, P., Fraboulet, D., Fahl, U., Mulholland, E., 2018. Perspectives on decarbonizing the transport sector in the EU-28. Energy Strategy Reviews 20, 124–132.

Hagos, D.A., Ahlgren, E.O., 2020. Exploring cost-effective transitions to fossil independent transportation in the future energy system of Denmark. Applied Energy 261, 114389.

Hansen,W., 2019. *Transport and the Spatial Economy: Developing a Spatial Computable General Equilibrium model for analysis of Wider economic impacts.* Theses for the PhD in Logistics at Molde University College.

Helgesen, P. I. 2013. Top-down and Bottom-up: Combining energy system models and macroeconomic general equilibrium models. CenSES working paper.

Helgeson, B., Peter, J., 2020. The role of electricity in decarbonizing European road transport–Development and assessment of an integrated multi-sectoral model. Applied Energy 262, 114365.

Hovi, I. B., Pinchasik, D. R., Thorne, R. J. & Figenbaum, E. 2019. User experiences from the early adopters of heavy-duty zero-emission vehicles in Norway: barriers and opportunities. Report 1734/2019.

Hovi, I.B., Mjøsund, C.S., Bø, E., Pinchasik, D.R., Grønland, S.E., 2021. Logistics, environment and costs - Vehicle data as a basis for research, transport planning and improvement work *(In Norwegian: Logistikk, miljø og kostnader - Kjøretøydata som grunnlag for forskning, transportplanlegging og forbedringsarbeid)*. Institute of Transport Economics. Report 1861/2021.

Hovi, I. B. 2018. Goods flows in Norway - a component of the National freight model *(In Norwegian: Varestrømmer i Norge–en komponent i Nasjonal godsmodell)*. Report 1628/2018.

Hyundai. *Hyundai XCIENT Fuel Cell Heads to Europe for Commercial Use* [Online].2020. Available: https://www.hyundai.news/eu/articles/press-releases/hyundai-xcient-fuel-cell-heads-to-europe-for-commercial-use.html.

IEA-ETSAP. *IEA-ETSAP Optimization Modeling Documentation* [Online].2022. Available: https://iea-etsap.org/index.php/documentation.

Islam, E., Moawad, A., Kim, N., Rousseau, A., 2018. An Extensive Study on Sizing, Energy Consumption, and Cost of Advanced Vehicle Technologies. Argonne National Lab. ANL), Argonne, IL (United States.

Jonkeren, O., Francke, J., Visser, J., 2019. A shift-share based tool for assessing the contribution of a modal shift to the decarbonisation of inland freight transport. European Transport Research Review 11, 1–15.

Kast, J., Morrison, G., Gangloff Jr, J.J., Vijayagopal, R., Marcinkoski, J., 2018. Designing hydrogen fuel cell electric trucks in a diverse medium and heavy duty market. Research in Transportation Economics 70, 139–147.

Leknes, S., Løkken, S., Syse, A. & Tønnessen, M. 2018. Befolkningsframskrivingene 2018. Modeller, forutsetninger og resultater [Population projections 2018. Statistisk sentralbyrå [Statistics Norway].

Carbon Limits 2019. The resource base for biogas production in Norway in 2030 (In Norwegian: Ressursgrunnlaget for produksjon av biogass i Norge i 2030 - Prosjekt for Miljødirektoratet). M-1533-2019.

Lovdata. *Forskrift om begrensning i bruk av helse- og miljøfarlige kjemikalier og andre produkter (produktforskriften)* [Online].2018. Lovdata. Available: https://lovdata.no/dokument/SF/forskrift/2004-06-01-922/KAPITTEL_4#%C2%A73-3.

Madslien, A., Steinsland, C. & Grønland, S. E. 2012. National freight transport model. An introduction to the use of the model *(In Norwegian: Nasjonal godstransportmodell. En innføring i bruk av modellen)*. Institute of Transport Economics. Report 1247/2012.

Madslien, A., Hovi, I.B., 2021. Projections for freight transport 2018–2050 (In Norwegian: Framskrivinger for godstransport 2018–2050. Oppdatering av beregninger fra 2019). Institute of. Transport Economics. Report 1825/2021.

Mareev, I., Becker, J., Sauer, D., 2017. Battery dimensioning and life cycle costs analysis for a heavy-duty truck considering the requirements of long-haul transportation. Energies 11, 55.

Martín, T., Luis, C., Santiago, G., 2019. A break-even analysis for battery electric trucks in Latin America. Journal of Cleaner Production 228, 1354–1367.

Meyer, T., 2020. Decarbonizing road freight transportation–A bibliometric and network analysis. Transportation Research Part D: Transport and Environment 89, 102619.

Ministry of Transport 2021. National Transport Plan 2022-2033 *(In Norwegian: Nasjonal transportplan 2022-2033)*. Meld.St. 20 (2020-2021).

Moll, C., Plötz, P., Hadwich, K., Wietschel, M., 2020. Are Battery-Electric Trucks for 24-Hour Delivery the Future of City Logistics?—A German Case Study. World Electric Vehicle Journal 11, 16.

Mulholland, E., Rogan, F., Gallachóir, B.Ó., 2017. From technology pathways to policy roadmaps to enabling measures–A multi-model approach. Energy 138, 1030–1041.

Mulholland, E., Teter, J., Cazzola, P., Mcdonald, Z., Gallachóir, Ó., B. p., 2018. The long haul towards decarbonising road freight – A global assessment to 2050. Applied Energy 216, 678–693.

Nordpool. *Historical Market Data* [Online].2020. Available: https://www.nordpoolgroup.com/historical-market-data/.

Norwegian Environment Agency 2020. Climate Cure 2030 — Measures and instruments towards 2030 *(In Norwegian: Klimakur 2030—Tiltak og virkemidler mot 2030)*. *M-1625/2020.*

Norwegian Environment Agency. *Environmental status (In Norwegian: Miljøstatus)* .2021. Miljødirektoratet. Available: https://miljostatus.miljodirektoratet.no/miljomal/klima.

Norwegian Ministry of Finance 2020. Perspektivmeldingen. Proposition for Parliament, nr. 14 (2020-2021). .

Norwegian Ministry of Transport and Comunications 2022. Endringer i vegtrafikkloven (krav til CO2-utslipp for tunge kjøretøy) og samtykke til godkjennelse av EØS-komiteens beslutninger nr. 396/2021 og nr. 398/2021 av 10. desember 2021 om innlemmelse i EØS-avtalen av forordning (EU) nr. 2018/956 og forordning (EU) nr. 2019/1242, med tilknyttede rettsakter. Prop. 106 LS, Norwegian Ministry of Transport and Comunications, Oslo.

NVE 2021. Long-term power market analysis 2021-2040 (Langsiktig kraftmarkedsanalyse 2021-2040). *In:* Norwegian Water Resources and Energy Directorate (ed.) *Report 29/2021.*

OFV. *Car year 2021. Figures and trends (In Norwegian: Bilåret 2021. Tall og trender)* [Online].2021. Available: https://s3-eu-west-1.amazonaws.com/opplysningsraadet-for-veitrafikk/images/Bil%C3%A5ret-2021-tall-og-trender.pdf.

Panoutsou, C., Germer, S., Karka, P., Papadokostantakis, S., Kroyan, Y., Wojcieszyk, M., Maniatis, K., Marchand, P., Landalv, I., 2021. Advanced biofuels to decarbonise European transport by 2030: Markets, challenges, and policies that impact their successful market uptake. Energy Strategy Reviews 34, 100633.

Pinchasik, D.R., Figenbaum, E., Hovi, I.B., Amundsen, A.H., 2021. Green Trucking? Technology Status, Costs, User Experiences. Institute of Transport Economics. Report 1855/2021.

Plötz, P., 2022. Hydrogen technology is unlikely to play a major role in sustainable road transport. Nature Electronics 5, 8–10.

Pye, S., Daly, H., 2015. Modelling sustainable urban travel in a whole systems energy model. Applied Energy 159, 97–107.

Rogers, E.M., 1962. Digusion of innovations. Free Press, New York.

Scania. *Scania launches fully electric truck with 250 km range* [Online].2020. Available: https://www.scania.com/group/en/home/newsroom/press-releases/press-release-detail-page.html/3768729-scania-launches-fully-electric-truck-with-250-km-range.

Sripad, S., Viswanathan, V., 2017. Performance metrics required of next-generation batteries to make a practical electric semi truck. ACS Energy Letters 2, 1669–1673.

Statens Vegvesen. *Updated status on zero-emission vehicles (In Norwegian: Oppdatert status på nullutslippskjøretøy)* [Online].2022. Statens vegvesen,. Available: https://www.vegvesen.no/fag/fokusomrader/miljovennlig-transport/nullutslippsmalene/.

Statistics Norway 2020b. Regional Population projections 2020-2050.

Statistics Norway. *Production and consumption of energy, energy balance and energy account* [Online].2020a. Available: https://www.ssb.no/energi-og-industri/statistikker/energibalanse.

Statistics Norway. *Kjørelengder, etter kjøretøytype, alder, statistikkvariabel og år. Statistikkbanken* [Online].2019. Available: https://www.ssb.no/statbank/table/12575.

Statnett 2020. Long-term market analysis - Nordic countries and Europe 2020-2050 (Langsiktig markedsanalyse - Norden og Europa 2020–2050).

Tesla 2017. Tesla Semi & Roadster Unveil. Available:https://www.youtube.com/watch?v=5RRmepp7i5g&ab_channel=Tesla.

Thiel, C., Nijs, W., Simoes, S., Schmidt, J., Van Zyl, A., Schmid, E., 2016. The impact of the EU car CO2 regulation on the energy system and the role of electro-mobility to achieve transport decarbonisation. Energy Policy 96, 153–166.

Tietge, Díaz, Mock, Bandivadekar, Dornoff & Ligterink 2019. From laboratory to road. A 2018 update of official and "real-word" fuel consumption and CO2 values for passenger cars in Europe. Berlin: ICCT.

European Union 2019. Regulation (EU) 2019/1242 - setting CO2 emission performance standards for new heavy-duty vehicles.

Venturini, G., Tattini, J., Mulholland, E., Gallachóir, B.Ó., 2019. Improvements in the representation of behavior in integrated energy and transport models. International Journal of Sustainable Transportation 13, 294–313.

Volvo, 2020. Volvo Trucks launches a complete range of electric trucks starting in Europe in 2021 [Online]. <https://www.volvogroup.com/en/news-and-media/news/2020/nov/news-3820395.html>.

Volvo. Volvo Group and Daimler Truck AG fully committed to hydrogen-based fuel-cells – launch of new joint venture cellcentric [Online], 2021. <https://www.volvogroup.com/en/news-and-media/news/2021/apr/news-3960135.html>.

Zhao, H., Wang, Q., Fulton, L., Jaller, M., Burke, A., 2018. A comparison of zero-emission highway trucking technologies. UCDavis.