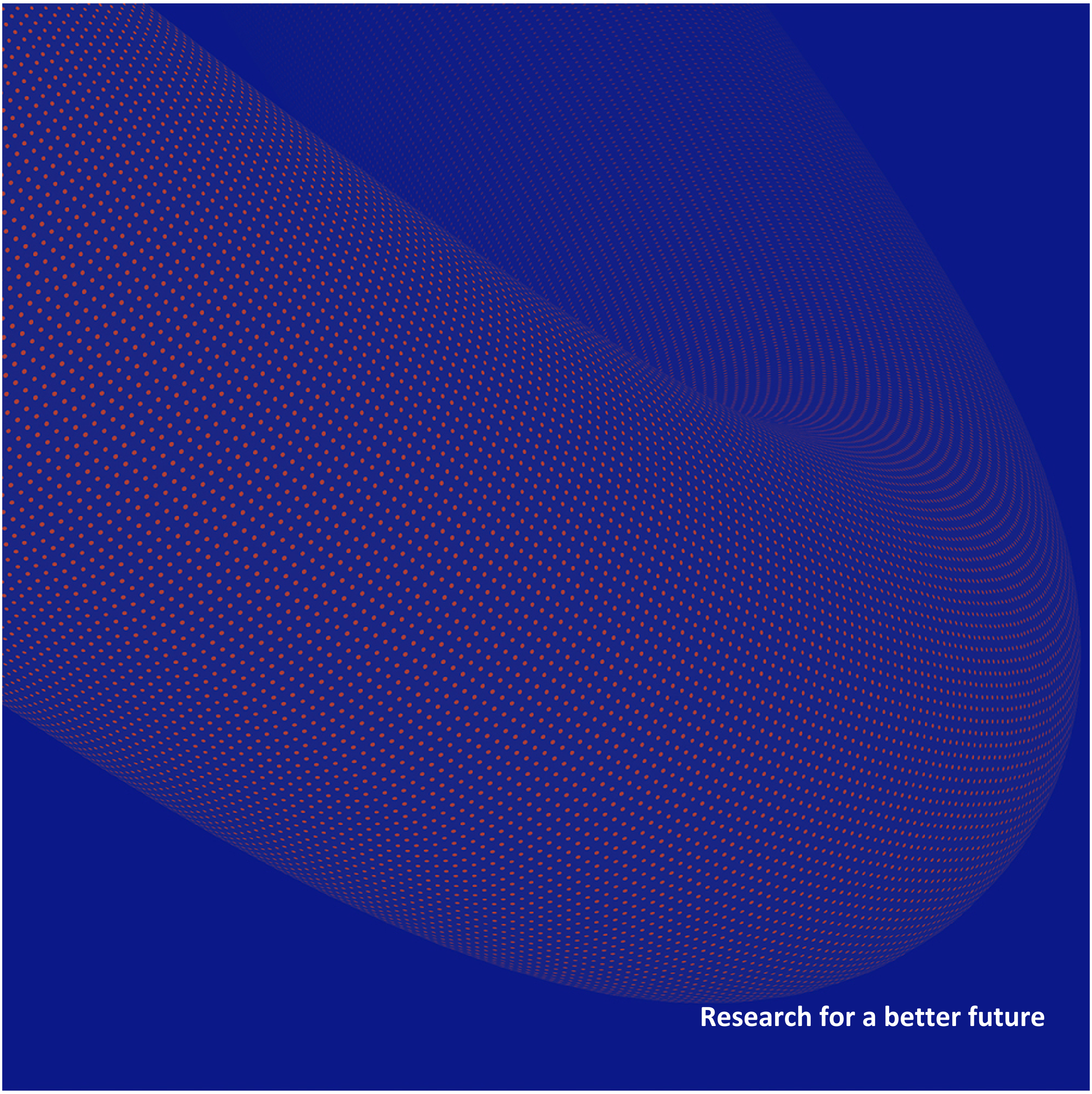
Impact of zero emission heavy-duty transport on the energy system

IFE/E-2021/002



Report number: **IFE/E-2021/002**	ISSN: 2535-6380	Availability: Public	Publication date: 2022-01-27
Revision:	ISBN: 978-82-7017-935-0	DOCUS-ID: 52115	Number of pages: 46

Client: Integrated Transport and Energy modelling, Research Council of Norway, project 280989

Title:

Impact of zero emission heavy-duty transport on the energy system

Summary:

To achieve Norway's climate targets (50% reduction by 2030 compared to 1990, and 90-95% reduction by 2050) emissions from the transport sector must be reduced significantly.

The Integrated Transport and Energy Modelling (ITEM) project has applied a two-pronged strategy consisting of (i) an in-depth analysis of the two most important transport corridors in Norway: Oslo-Bergen and Oslo-Trondheim, and (ii) a national modelling framework integrating energy system models with improved vehicle, travel, and freight demand models.

Two main scenarios have been analyzed: **Slow** (with present energy and climate policies) and **Fast** (with higher CO2 tax and more policy measures). While the energy use for trucks decrease, due to improved energy efficiency of new vehicles, particularly battery electric vehicles, the demand for electricity and hydrogen will increase. Electricity demand in transport increases from present level at 2 TWh to 19 TWh in 2050 in the Fast scenario. The CO2-emissions from transportation decrease in all analysed scenarios. Decreasing emissions from transport in line with the climate targets is only possible with an optimistic technology development and an optimized behaviour. Alternatively, climate targets can be met by implementation of targeted policy measures.

From the local scale analyses, we observe that the energy demand for fast charging and refuelling in the corridors increase from 15-40 GWh in 2030 to 160-450 GWh in 2050 with 100% zero-emission truck fleet. The corresponding peak demand for the charging/refuelling station increases from 5-9 MW in 2030 to 50-110 MW in 2050.

Electrification of transport contributes to the sector coupling between the power and the transport sector. Both the electricity demand increases and the volatility in power increases due to charging and hydrogen production.

The modelling, analysis and conclusions discussed in this report are from the energy systems analysis on the transport corridor level and on the national level.

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Executive summary

A transition to zero and low emission technology in transport is needed. Large potential for greenhouse gas abatement in transport lies in electrification. For road vehicles the possible zero emission technologies battery electric vehicles and hydrogen fuel cell electric vehicles, will result in increased demand for electricity and for regional and local grid capacity when hydrogen is produced by electrolysis. An electrified road sector will imply a more complex interaction between the markets for renewable power and transport.

The ITEM project has analyzed policies and measures suited to reach Norwegian political targets regarding carbon neutrality and GHG abatement in the transport sector. The project has applied a two-pronged strategy consisting of in (i) an in-depth analysis of the two most important transport corridors in Norway: Oslo-Bergen and Oslo-Trondheim, and (ii) a hybrid modeling framework integrating energy system models with improved vehicle, travel and freight demand models, to provide enhanced policy support tools.

The ITEM project study the energy use of heavy transport by use of several models. The main ones are a transport demand model (NGM, operated by TØI), a fleet-stock model (BIG, operated by TØI), a national energy system model (IFE-TIMES-Norway, operated by IFE) and local energy system models of energy stations (operated by IFE).

At the local scale, we have modelled energy stations connected to the distribution grid, to study the size of different energy stations depending on future transport demand. By modelling at local level, e.g., a single energy station, both an hourly time resolution can be used as well as a component modelling of the energy station. Insights from this detailed modelling is transferred to the national energy system model. The interaction between the national and the local energy system model provides the national energy system model with more detailed insights, and thereby improve the national energy system model.

In the transport corridors (local scale) we have analysed three localisations (Hanestad, Otta and Gol) for charging and refuelling in two scenarios which both have an increasing share of ZE trucks, increasing to 100% in 2050. One scenario uses both hydrogen and battery electric trucks, and scenario one where only battery electric trucks are used. The results show that the energy demand for fast charging and refuelling in the corridors are in the range of 15-40 GWh in 2030 increasing to 160 to 450 GWh in 2050 in analysis with 100% zero-emission truck fleet. In H2+BEV scenario the energy demand is notably larger than in BEV only scenario, due to more energy efficient technology as well as assumed adoption of charging at depots. The grid would be exposed to 5-9 MW peak demand from a charging/refuelling station in 2030, which increases to 50-110 MW in 2050. The results are relatively similar for the BEV+H2 and the BEV only scenario. Similar peak demand, while lower energy demand, in the BEV only scenario implies that power demand from the grid will be much more volatile in the BEV only scenario. The figure shows the grid connection for the three energy stations analysed.

At the national level, we have analyzed the impacts of zero emission heavy-duty transport on the energy system and future CO2 emission from the transport sector under different scenario assumptions with respect to technology development, future CO2 prices, transport demand etc. The two main scenarios we have analyzed are:

1. **Slow** with present energy and climate policies
2. **Fast** with higher CO2 tax and stronger energy and climate policy measures.

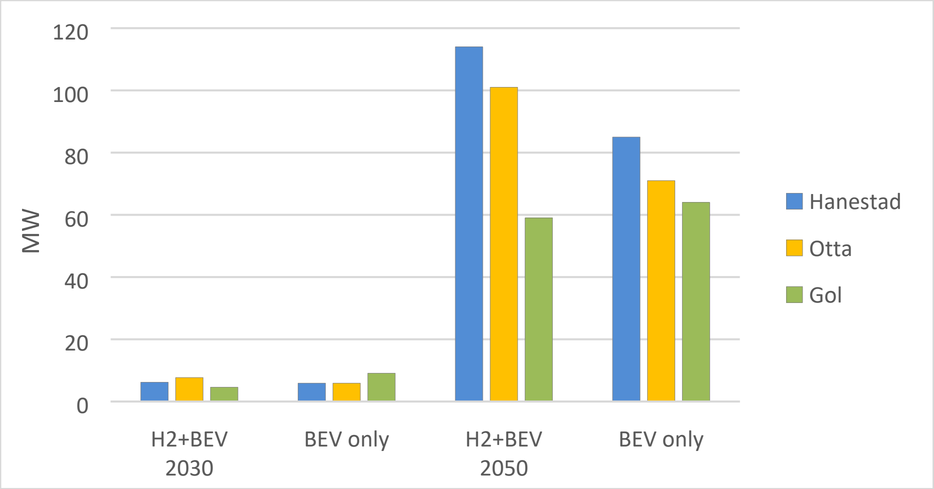


Figure i: Grid connection of energy station for 2030 and 2050 in two scenarios

While the energy use for trucks decrease, due to improved energy efficiency of new vehicles, particularly battery electric vehicles, the demand for electricity and hydrogen will increase. Electricity demand in transport increases from present level at 2 TWh to 19 TWh in 2050 in the Fast scenario. In the Slow scenario the implementation of ZE trucks is slower, and there is still a share of conventional vehicles (ICE) in 2050.

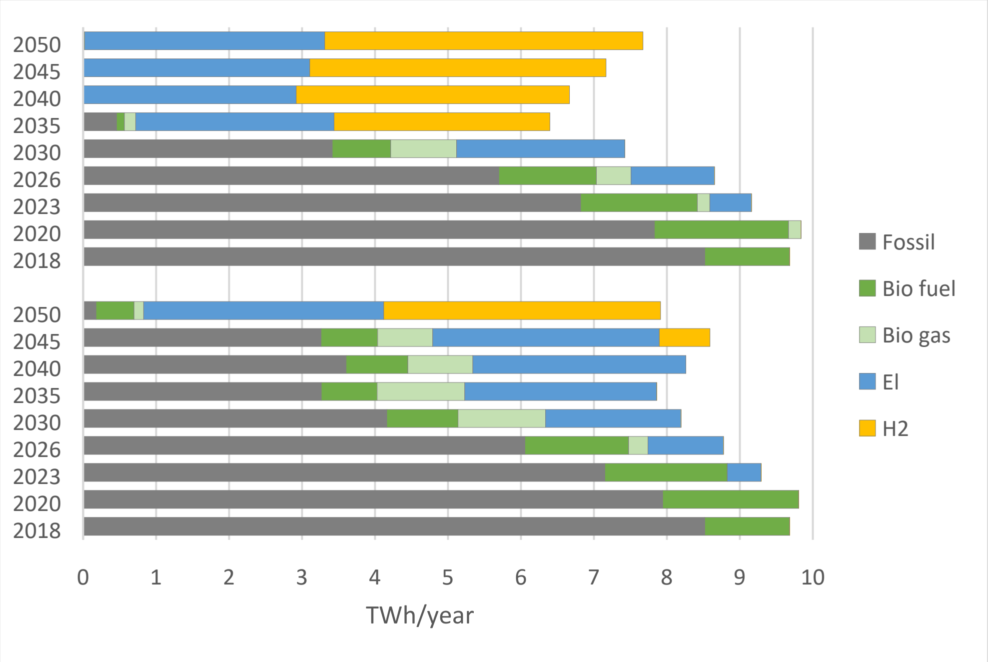


Figure ii: Energy use in the transport sector (TWh/year) in the Slow and Fast scenario

In the national analysis we have analyzed the impact of different policy measures, and the results indicates that we need continued and fast technology development, and an optimized behavior to reach the emission targets for the transport sector. Also, biofuels can contribute to reduced emission from the transport sector. However, more detailed studies of bio energy, and in which sectors a limited resource as bio energy should be used, are needed. Climate targets can also be met by implementation of targeted policy measures such as investment support, other financial support measures and/or taxes.

1 Introduction

A transition to zero and low emission technology in transport is needed. Large potential for greenhouse gas abatement in transport lies in electrification. The project Integrated Transport and Energy Modelling (ITEM) aims to determine which policies and measures are best suited to reach Norwegian political targets regarding carbon neutrality and GHG abatement in the transport sector. The project has applied a two-pronged strategy consisting of (i) an in-depth analysis of the two most important transport corridors in Norway: Oslo-Bergen and Oslo-Trondheim, and (ii) a hybrid modelling framework integrating energy system models with improved vehicle, travel and freight demand models, to provide enhanced policy support tools.

For road vehicles, the possible zero emission technologies battery electric vehicles and hydrogen fuel cell electric vehicles will result in increased demand for electricity and for regional and local grid capacity when hydrogen is produced by electrolysis. Also, catenary, or other along-the-road electric charging will increase the demand for electricity, but these technologies have not been included in this study. An electrified road sector will imply a more complex interaction between the markets for renewable power and transport.

ITEM is a competence project with three research partners and ten user partners, coordinated by Institute for Energy Technology (IFE), and with Institute of Transport Economics (TOI) as the main research partner. University of California, Davis is the international research partner. User partners are Enova, Hallingdal Kraftnett, Eidsiva Nett, Statkraft, Mer (tidligere Grønn Kontakt), Scania, Lastebileierforbundet, NHO, Statens Vegvesen and Recharge (tidligere Fortum Charge & Drive).

This report presents work done by IFE, where we investigate what are the main technical, economical and policy aspects which will affect the deployment of zero emission trucks and how will the Norwegian energy system be affected by a large-scale deployment of zero emission trucks.

1.1 Importance and ambitions to reach low emissions road transport

Norway has bind itself to several international, EU and national level agreements to limit the global warming. The international Paris agreement with ambition to limit the global warming well below 2°C sets the bar for the Norwegian ambition level for climate policies. To comply with the agreement Norway has together with EU recently adjusted a common goal of greenhouse gas reduction by at least 50% by 2030 compared to 1990, to be in line with the Paris agreement [1]. At EU level there is an ongoing process to increase even further the ambition level with a binding greenhouse gas cut of 55% compared to 1990 within the “Fit for 55” package [2].

In a longer perspective, Norway has set the ambition to become a low emission society (CO2 emission reduction by 90-95%) by 2050, which is also in line with the EU climate neutrality vision by the same year [1, 3].

At EU level the emissions are divided between those who are included in the EU Emission Trading Scheme (ETS) and those who are not. The emissions traded within ETS, such as industry, air traffic and parts of power production, is agreed to be reduced on a European level. While the emissions not part of ETS, such as road transport, shall be reduced nationally. About half of the Norwegian emissions are non-ETS and the national ambitions are to reduce them by 45% by 2030. [1]

The transport sector emitted almost 16 million tons of CO2 in 2020 and by that accounted for 32% of the national emissions of greenhouse gases and 60% of the non-ETS emissions. The national ambition is to reduce them by 50% by 2030. A cleaner transport sector would also contribute to reduce the local pollutions such as NOx and particles. However, recent analysis shows that current policies are not sufficient to neither reach the goal of sufficient emission reduction by 2030 or to decarbonize the transport sector by 2050. [4-6]

Heavy-duty trucks are responsible for approx. 16% of the emissions of greenhouse gases in the transport sector, with only private cars and sea transport as bigger emitters. Their emissions of greenhouse gases have increased by approx. 85% between 1990 and 2018 while the road freight (in ton-km) increased by approx. 140% in the same period. The current challenge is a further expected growth with approx. 70% increase in ton-km until 2050 at the same time as the emissions should rapidly decrease this decade and be eliminated by 2050. [4, 7, 8]

1.2 Relevant Norwegian and EU policies

Several national and European policies impact the transport segment. In Norway especially the battery electric passenger vehicles have been strongly promoted by several benefits, where the exemption of one-time fee and purchase tax is the most notable ones. However, in this chapter the relevant policies affecting the Norwegian heavy duty road transport will be highlighted.

When considering the purchase of the more expensive zero-emission trucks, the Norwegian state wants to encourage early adapters by covering up to 40-50% of additional costs when investing in battery, hydrogen, and biogas powered trucks, as well as their infrastructure for charging or refueling [9].

The EU-regulation 2019/1242 sets an obligatory CO2 emission reduction per ton kilometer (ton-km) of transported goods for new vehicles, to force the producers to sell less pollutant vehicles. It applies for the most common truck types in EU (2x4 and 2x6 configurations of tractor and rigid truck types) and aims for 15% reduction in 2025 and additional 15% until 2030 relative to the values of 2019. The same regulation enables also increased vehicle weight up to 2 tons for zero emission vehicles to compensate for heavier powertrain in comparison with the conventional ones. [10]

Even if the above-mentioned regulation currently is only relevant for EU states, it will most likely also be implemented among the EEA states, including Norway.

In addition to support the initial investments, there are several initiatives to improve the competitiveness of the more sustainable transport alternatives, such as the national carbon tax of 590 NOK/ton$_{CO2}$ on fossil fuels. In the latest Norwegian climate plan this tax is suggested to be increased to 2000 NOK/ton$_{CO2}$, while current policies intend to offset the increased tax pressure on fossil road fuels by reducing road taxes [5]. Other ways zero-emission heavy duty transport is favoured is for example through exempts from road tolls in the largest cities.

1.3 Current status of ZE truck technology

The liquid fuels have a superior volumetric and gravimetric density of energy storage, and the internal combustion engine offers a reliable and economic powertrain. For other powertrain alternatives it has been very difficult to compete with the status quo. For battery electric trucks the battery has been the main limitation, especially considering cost and gravimetric energy density and possibly lifetime [11, 12]. While for fuel cell electric trucks the cost of fuel cell, hydrogen tank volumes and hydrogen prices are important limitations to compete with ICE [13, 14].

The option of using renewable fuels in ICE is limited by its local emissions due to combustion, limited access to sustainably sourced fuel and costs of the fuel. It makes it complementary to battery and fuel cell electric vehicles where a superior range or storage density is essential. [15]

When Tesla's unrevealed their long-haulage truck, Semi, in 2017, its range and performance was beyond of what was believed realistic at that time [16, 17]. So, it became an important step towards the inclusion of batteries as a realistic option for truck decarbonization. Even if by today (2021) the Tesla Semi is still not available for sale, several established OEMs (Original Equipment Manufacturer) have begun to series produce battery electric heavy-duty trucks, thus with a range well below what was announced for the Tesla Semi [18-21]. However, it is worth to notice that almost 60% of the total daily milage in Norway made by newer trucks (<5 years) has a daily trip length of 300 km or less [22].

Recent studies shows how battery electric trucks could become cost competitive [23, 24], even though range and battery costs makes the long-haulage segment be the most difficult to electrify [15, 25, 26]. When taking into account fast charging at the European obligatory brakes after 4,5 h driving time, relevant average driving velocity for Norway (65 km/h) and evaluating the costs based on ton km of goods transported, the heaviest trucks (including vehicles up to 100 ton GVW) becomes the most feasible to convert [27].

Hydrogen used in fuel cells has been seen as another feasible pathway to decarbonize transport sector, mainly due to a higher gravimetric density of energy storage and fast refueling in comparison with charging [11, 28]. The development of such trucks was initiated by start-up companies, such as Nikola, and one-of rebuilds for demonstration, such as Asko [29]. During the last years fuel cell trucks have gained moment as OEM like Hyundai already delivers hydrogen powered heavy-duty trucks to Switzerland [30] and the joint venture Cellcentric by Daimler and Volvo to accelerate hydrogen powertrain development [31].

As several of OEM's who are already well established in Norway offer series produced battery electric trucks, a recent increase in their deployment has been observed.

To accelerate the decarbonization of road freight in Norway several national initiatives have developed, where "Grønt landtransportprogram" has an aim to facilitate the introduction. In one of its pilot projects the freight industry has shown interest to electrify 300 trucks by 2023 [32]. Another initiative is H2Truck which has gathered a broad consortium of actors in the entire supply chain and is aiming to introduce the first 100 hydrogen trucks in the Oslo area from several suppliers [33].

The charging infrastructure for trucks can be categorized both by charging speed (slow or fast) and by location (at depot or in-route). In general, slow charging is associated with logistic depos, while fast charging is done along the road. However, it might also be a demand for fast charging at depos if that can increase the truck utilization rate and slow charging during the trip if overnight stop is part of the journey. Whenever possible, slow depot charging is preferred as it is the simplest way considering the logistics as well as the cheapest option. [34]

The impact on the grid both from fast chargers along routes as well as slow chargers at depots has been investigated in different international settings. Smart depot charging for fleets of up to 100 vehicles required upgrades of the Texas (USA) grid only in approx. 20% of the 36 substations studied [35], while an existing substation in the transport corridor Oslo-Trondheim could absorb the power demand if a share of up to 25% of current volume of heavy-duty trucks would stop for fast-charging [36].

[37] found that BEV could serve 71% of Swiss ton-kilometers, while only 35% of the Finnish ton-kilometers with the most electrification friendly scenario and that it only would increase the national

energy demand by 1-3%. However, in the case of Switzerland a simultaneous depot charging would imply a power demand corresponding up to 57% of the average electricity load in 2016.

The previous studies shows that the additional load from electric trucks can to large extent be in cooperated in the grid, while challenges could occur locally.

The hydrogen supply to transport sector has a distinct impact on the grid hence it can be produced continuously in contrast to peaky demand of charging. The production can also be separated from the refueling station, enabling it to be located where the grid is stronger [38]. The trade off, from the energy system point of view, is that hydrogen production and utilization in the transport sector requires more energy in comparison with direct electrification.

1.4 Forecasts of decarbonisation of transport sector

A review of various national forecast estimates (NVE's "Langsiktig kraftmarkedsanalyse" [39], Statnett's "Langsiktig markedsanalyse" [40], DNV's "Energy Transition Norway 2021" [41]) shows a relatively homogenous picture, when considering their main scenario. The analysis made by NVE and Statnett indicates that the transport sector will have an electricity demand of 15 TWh by 2040, which in the Statnett prediction increase to 20 TWh by 2050. While analysis by DNV assumes slightly lower demand in 2050 of approx. 18.5 TWh. It was however only in the analysis of DNV where the total energy demand of commercial road transport was specified, approx. 14 TWh in 2050 under assumption that 90% of it would be electric. Hydrogen as a possible energy carrier for more energy intensive transport means in general are mentioned in all three reports, while only NVE specifies its possible use in heavy-duty road freight.

2 Methodology

The ITEM project study the energy use of heavy transport by use of several models. The main ones are a transport demand model (NGM, operated by TØI), a fleet-stock model (BIG, operated by TØI), a national energy system model (IFE-TIMES-Norway, operated by IFE) and local energy system models of energy stations (operated by IFE). Nation-wide models such as IFE-TIMES-Norway aggregate end-use sectors in order to keep the model size at a reasonable level. The time resolution must be high enough to give reasonable results, but also coarse enough to give a reasonable computational time. This can result in loss of information on a detailed level of both rapid changes in energy prices and demand. By modelling at local level, e.g., a single energy station, both an hourly time resolution can be used as well as a component modelling of the energy station. Insights from this detailed modelling is transferred to the nation-wide model, thereby reducing the limitations a national model might give. The interaction between the national and the local energy system models provides the national energy system model with more detailed insights in some technologies, and thereby improving the national energy system model.

This IFE-report is a documentation of the analysis done by IFE in the project, while TØI has documented their analysis in the report “Forsering eller hvileskjær? Om utsiktene til klimagasskutt i veitransporten” (*in Norwegian*) [6]. IFE and TØI have harmonized the input data in the analysis, and IFE have used data on transport demand from TØI. However, the analysis has not been done with linked models. The analysis performed with the transport and energy models aim at increasing our understanding on how we can have a transition towards zero emission in the transport sector. In addition, the analysis at IFE includes analysis of the impacts on the energy system on this transition in transport.

The research related to linking the transport and energy models is still ongoing and will be documented in a scientific paper. As no model is perfect, the hypothesis of this project is that by interaction between these models, an improved insight on how to be able to implement a transition to a fossil-free transportation of heavy-duty vehicles, will be achieved. Reasons for the linking/interaction between the models are that:

- Optimalisation models often results in an unrealistically high implementation of new technologies
- Stock-models may have problems with introduction of new technologies due to lack of statistics and few or no of the new technologies in the base year
- Linking can provide the optimization model with growth constraints and the stock-model with data on new technologies

3 Local analysis

The forecasts of national development of road transport are also of relevance to explore in a more local setting to understand better the local impact on the energy system. An especial interest is in locations where large volume of goods transport is occurring, such as main transport corridors. In this local analysis the possible annual energy demand, power demand and optimal energy station layout in the transport corridors Oslo-Bergen and Oslo-Trondheim, have been evaluated.

3.1 Background

To the authors knowledge there has not yet been made any estimates on how the grid can be affected locally by heavy duty vehicle transition towards zero emission technology, with focus on fast charging and the increase in demand over time in Norway. Fast charging of heavy duty vehicles has been identified as demanding to accommodate in the existing grid [36, 42], which sometimes is presented as a significant barrier [43]. While others argue that utilisation rate is more important than power outtake [44].

To understand the impact of charging upon the local grid, it can be evaluated at different resolution. [36] made an analysis of how power demand for heavy-duty fast charger can vary considering a minute resolution. Their analysis was based on the transport corridor Oslo-Trondheim via Østerdalen, and its result can be seen in Figure 1. The result shows significant intra-hour variation for charging, based on the expected random utilization of the infrastructure based on existing driving patterns.

On the other hand, hydrogen production will preferably be operated at relatively constant pace to assure high utilization rate of the expensive equipment [45].

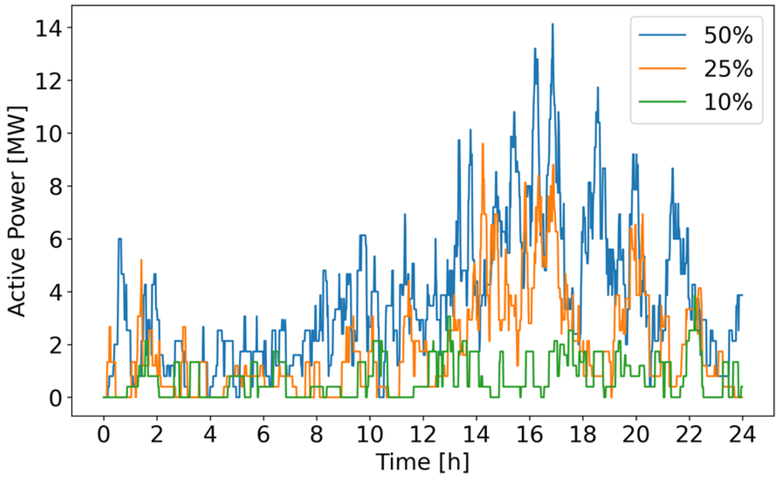


Figure 1 Modelling of variation in energy demand at charger station with minute resolution in case 10%, 25% or 50% of today's trucks passing selected location would be battery electric and need fast charging.[36]

3.2 Data sources

3.2.1 Traffic count

The Norwegian Public Road Administration (NPRA) has an extensive grid of inductive sensors on road which counts vehicle passing and their velocity [46]. Vehicle types can to some extent be deducted from vehicle length, see a possible approximation in Figure 2. As it can be observed, lot of different vehicle types have overlapping lengths. In addition, the accuracy of vehicle length measurement through the equipment used by NPRA is unknown.

Considering the uncertainty of vehicle types measured below 12.5 m, the truck movement patterns in this analysis is based only on data for trucks above 16 m. Due to the lack of data for trucks without trailer, in this analysis they are assumed to have similar driving patterns as vehicles with trailer. This assumption has its flaws as more local transport probably occurs within working hours with trucks without trailer, in comparison with long-haul transport which typically will have some kind of trailer and have operation time which is more detached from typical working hours. Different locations have also a variation when there is most frequent traffic of trucks with trailer and their share of total traffic volume, for example between city/logistic hub and in the middle of a transport corridor.

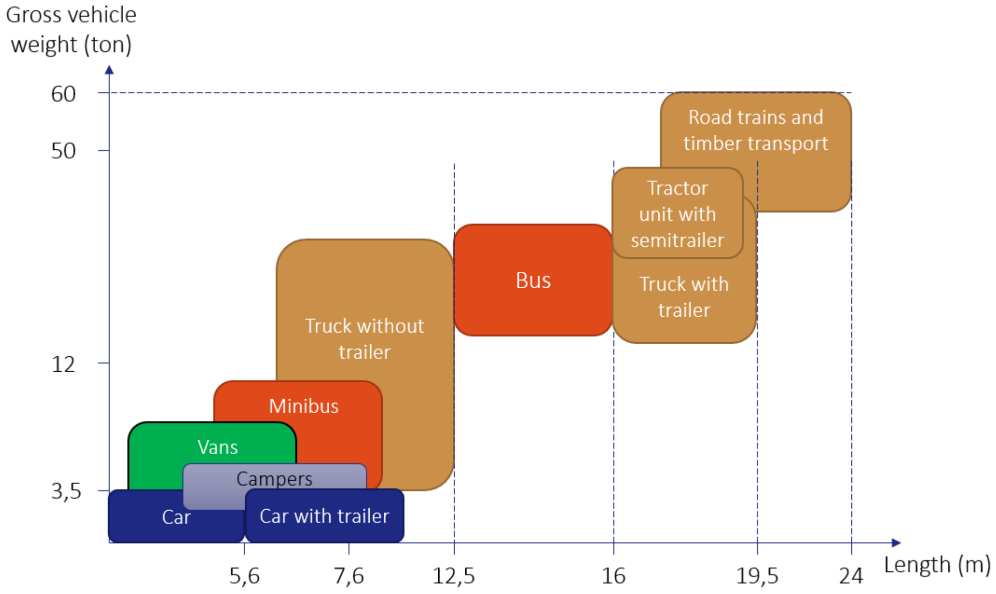


Figure 2 Estimated correlation between vehicle length and vehicle type and size

3.2.2 National freight model

The Institute of Transport Economics operates a detailed national freight model which indicates how goods are transported considering road, rail, and sea transport. It has a geographical resolution at municipality level and international locations. The freight is modelled at an annual resolution and considers existing transport infrastructure and the one which is in construction phases. In addition, it includes 39 goods categories and various vehicle/vessel types. With known freight demand to and from each municipality, the model is able to show the most efficient way to transport the goods nationally and abroad.

3.2.3 LIMCO project

Through research project “Logistic requirements, environment and costs” led by The Institute of Transport Economics and funded by Norwegian Research Council, data of truck operation patterns were gathered through GPS loggers. The aim of the project was to evaluate improvements in the truck logistics of several large truck fleet operators. However, it also provides aggregated data of truck driving patterns, which is valuable to assessing todays and tomorrow’s infrastructure demands.

3.3 Methodology and assumptions

The local analysis was made in three steps as shown in Figure 3. To make the analysis, some initial assumptions are needed (0a and 0b). Based on the uncertainty in the assumptions several scenarios are developed to cover a range of possible outcomes. The different scenarios in the analysis are based on different technical and market assumptions which changes over time from 2030 to 2050. The technical assumptions diverse into either a full electric future or a case where both electric and hydrogen trucks are used. In addition, the range of the different vehicles are changing over time. The market scenario is also time dependent, where in 2030 only a share of vehicles is assumed to be zero emission, but by 2050 a fully emission free truck fleet is expected.

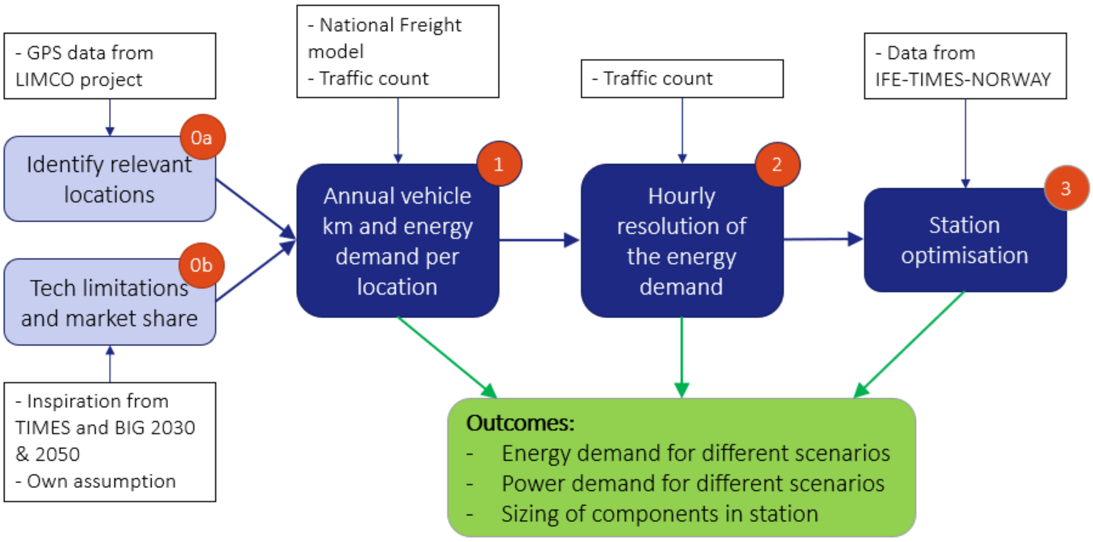


Figure 3 Workflow chart of local analysis

Once relevant locations are selected and technical limitations were set, data from the national freight model was assessed to quantify vehicle travelling patterns in selected locations with focus on trip length. To quality check the data output, the model output was compared to traffic counts in 2018 and adjusted accordingly. Based on the technical and market assumptions for the trucks, an annual energy demand was assessed.

To understand better the energy demand effect on the grid, the annual energy demand was disaggregated into an hourly resolution with help of the traffic count for vehicles longer than 16 m.

With this hourly demand profile and cost data taken from IFE-TIMES-Norway, an optimised energy station was identified considering the costs of grid connection, local hydrogen production and local battery.

3.3.1 Location

To identify relevant locations to study, both GPS data from several trucks from main logistic companies gathered by TØI in the LIMCO project was used as well as assessment by the authors.

For the corridor Oslo – Bergen, the main locations of stops of long-distance drivers (>4h) from GPS data were Gol, Lærdal and nearby Vøringsfossen in Hardangervidda. The traffic from all three points is most probably passing Gol, where a notable number of drivers stops. Thereby this location was chosen as suitable for the transport corridor Oslo-Bergen.

For the corridor Oslo – Trondheim, there are substantial flow of road freight both in the E6 through Gudbrandsdalen and Rv3 through Østerdalen. The main flow from south towards Trondheim and further north will prefer Rv3 as it is the fastest route, while E6 is used in larger extent for freight towards northern parts of Western Norway (Ålesund, Molde, Florø, etc.) and within Gudbrandsdalen. To assess both these freight streams Hanestad on Rv3 and Otta on E6 were selected. Even if GPS data does not show many stops in Otta, it is concluded as a relevant location as some of the freight volumes diverges here on Rv15 towards Stryn and it takes approx. 4h to arrive to Otta from Oslo, which suits relatively well for a break.

Figure 4 Heat map of where trucks stop for more than 30 min after been driving at least 4 hours. In addition, shows selected location for analysis.

3.3.2 Tech limitations and market share

The role of zero emission transport has been assessed both with TØIs stock-flow cohort model BIG and national energy system model IFE-TIMES-Norway. Both models show increase in zero-emission freight, especially in a fast decarbonization scenario. These are however national scenarios, where local deviation will occur. The local variation can have various reasons, such as distribution of vehicle size, trip length, available infrastructure, and political effort to decarbonize faster certain routes/areas.

When considering fast decarbonization pathway analysis made with BIG, electricity and hydrogen serves 12% of the total vehicle km in 2030 and 93% by 2050. The TIMES analysis shows a more rapid increase (see chapter 4 National analyses), and hydrogen and electricity reach almost 50% in 2030 and 100% in 2050 of the total vehicle km.

As BEV seems to be a more economical, but with challenges to reach large distances, they are assumed to conquest short distance trips, while FCEV expand in replacing heavy duty vehicles used for long distance trips. In the BEV only scenario the technology of BEV and its market share is assumed to advance in a slightly higher pace. Due to FCEV currently lagging development relative to BEV, they are assumed to have a lower market penetration in 2030.

Considering the limitation in range for zero-emission technologies when compared to diesel, it is highly probable that efforts will be made to limit the range anxiety. Slow charging at depots becomes a great opportunity to reduce the range limitations as well as it is assumably the cheapest way to charge the vehicle. This aspect is included in the analysis by assuming that all BEV start their trip fully charged and that no fast charging is done for trips well within the range of the BEV.

On the other hand, hydrogen refueling station are more expensive to install, but can efficiently refuel large energy quantities. This particularity is included in the analysis by assuming that trucks departing from larger logistic hubs (Oslo, Bergen and Trondheim) will be fully fuelled up and will not need refueling in the middle of the studied transport corridors. While the rest of the FCEV will be interested in refueling corresponding their trip length and that they have as a minimum always 10% of their range capacity left when they refuel.

In Table 1 & Table 2 the assumptions and thresholds described above and used to estimate energy demand at given locations are summarized. Of all trips suitable for BEV, based on a trip length, it is assumed that BEV will be used in 35% of the cases in 2030. The corresponding share for trips assumed suitable for hydrogen is 10%. By 2050, both BEV and FCEV are assumed to stand for 100% of the trips within their assigned trip lengths.

Table 1 Assumption on for which trips and how much BEV and FCEV will be charged/refueled in 2030 and 2050

Year	Trip length	Energy carrier	Driving distance refuelled at station
2030	>300 km	H2	= Trip length, but max 500 km
	100-300 km	Battery	= Distance from the start of trip, but max 90% SoC
	<100 km		Excluded as only depot charging assumed
2050	>500 km	H2	= Trip length, but max 800 km
	200-500 km	Battery	= Distance from the start of trip
	<200 km		Excluded as only depot charging assumed

Table 2 Assumption on for which trips and how much BEV will be charged in the battery only scenario in 2030 and 2050

Year	Trip length	Energy carrier	Driving distance refuelled at station
2030	>500 km	Not covered	
	100-500 km	Battery	= Distance from the start of trip, but max 90% SoC
	<100 km		Excluded as only depot charging assumed
2050	>200 km	Battery	= Distance from the start of trip, but max 90% SoC
	<200 km		Excluded as only depot charging assumed

The energy efficiency from tank to wheel is assumed to be in average 1.75 kWh/km for BEV and 2.9 kWh/km for FCEV.

3.4 Results

The main results of the local analysis are presented in this chapter. First, the estimated energy demand at chosen locations is presented, then a representative hourly demand profile is identified. Finally, a local energy station is modelled where energy buffer demand is optimised in form of hydrogen and battery storage.

3.4.1 Energy demand

In Figure 5 & Figure 6 is shown the estimated energy demand at each location based on demand forecasted in selected locations with help of NGM. The energy represents fuel charged into the vehicle and does not account for efficiency loss in the charger nor electricity required for hydrogen production. Note that as zero-emission technology serves the entire transport demand by 2050 together with increased demand, the energy demand in most cases more than tenfold between 2030 and 2050, and the two largest stations have an energy demand around 500 GWh in 2050 in the H2+BEV scenario, while only 200 GWh in the Only-BEV scenario.

More detailed analysis of the data received by NGM is shown in Appendix A, where it is shown how the traffic volume is distributed distinctly of different trip lengths. It has also been identified that trips going through these three locations contributes with 19% to the total national vehicle kilometres.

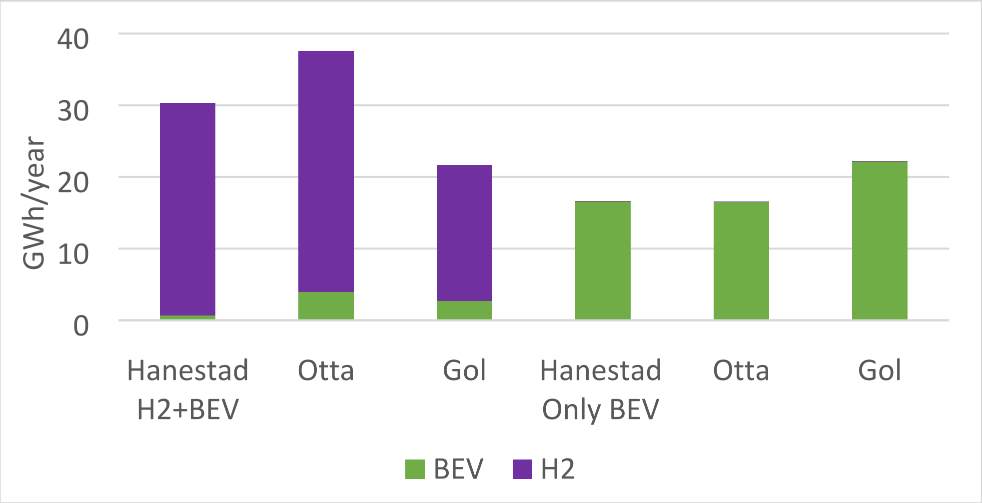


Figure 5 Estimated annual energy demand in 2030 for trucks in H2+BEV and Only BEV scenario

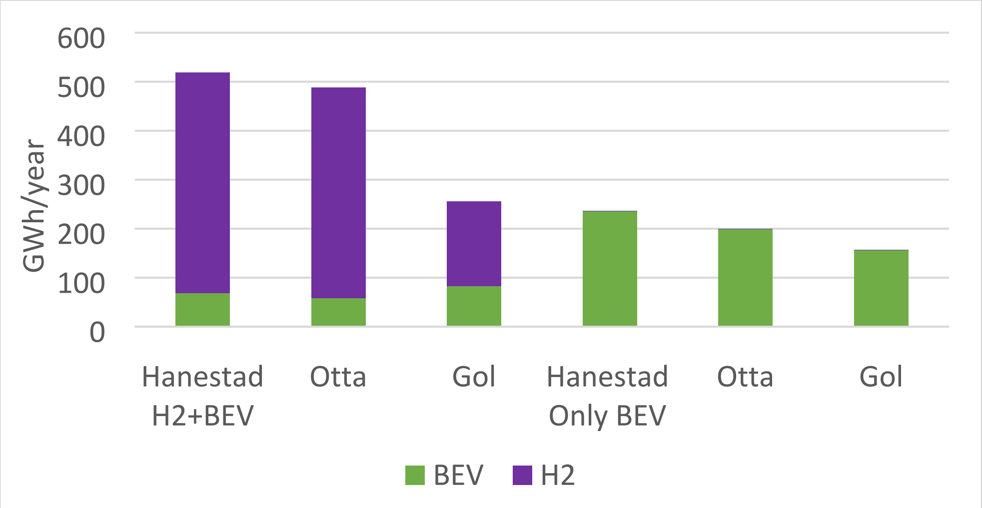


Figure 6 Estimated annual energy demand in 2050 for trucks in H2+BEV and Only BEV scenario

3.4.2 Hourly profile

To transform the annual energy demand into an hourly resolution, sites for vehicle count was selected based on nearest sites with satisfying data quality. The selected sites are listed in Table 3. For Otta and Gol, where several roads are joining, a station which is located slightly to the south of such joint is selected considering the concentration of traffic flow towards Oslo region and for traffic towards Europe, passing by Oslo.

The most recent complete traffic count year was selected prior 2020, excluding possible Covid pandemic effects in 2020.

Table 3 Shows which vehicle counting sites were used and year of time serie

Location	**Name of vehicle counting site**	**Year**
Hanestad	Hanekampen	2017
Otta	Sjoa Bomstasjon	2019
Gol	Flå Syd	2019

In Figure 7 is shown how the distribution of counts are occurring when seen with a weekly resolution. The pattern is relatively consistent at this resolution with lowest traffic during Saturday and with clear increase in traffic during Sunday afternoon. Even if this illustration shows the activity at Otta, very similar patterns where also found for Hanestad and Gol.

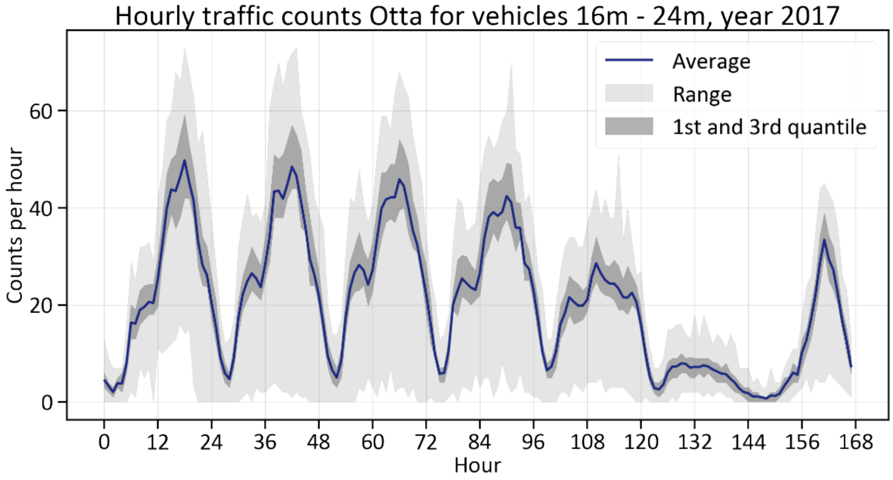


Figure 7 Average and the spectrum of the traffic flow over a week for each location.

The availability of charging and refueling infrastructure to serve zero-emission commercial vehicles is important as waiting time of drivers and unforeseen events in logistics scheduling are important cost drivers for truck operators. So, the charging infrastructure should provide efficient service considering both day to day variabilities throughout the year shown in Figure 7 and expected daily variability shown in Figure 1.

On the other hand, the infrastructure will both be a high in front investment in the transition towards sustainable road transport and they will probably face practical challenges to keep pace with increasing demand. Practical challenges could for example be to find an attractive location for truck drivers considering both space and access to grid to provide charging and refueling services.

In this work is assumed that logistic operators will adopt to some extent to the constraints zero-emission vehicles bring in form of more detailed planning of charging in comparison with internal combustion engines. This adoption is included by flattening the intra-hour variation of demand, while annual demand variation with few extreme peaks is included. From the assumption of a flat intra-hour energy consumption of the station's peak hour and traffic count, the capacity factors and representative peak hour is shown in Table 4.

Table 4 Capacity factors as well as peak power in a BEV only scenario

Location	Capacity factor	2030		2050	
		Annual energy (GWh)	Peak power (MW)	Annual energy (GWh)	Peak power (MW)
Hanestad	0.25	17	7.6	236	108
Otta	0.28	17	6.7	199	81
Gol	0.25	22	10	156	71

3.4.3 System optimisation and power demand

The local energy system is modelled with a linear programming optimization model using TIMES framework. In Figure 8 how the model is set up is presented. The cost assumption for the different components is based on prices expected in 2030 and hourly power price is taken from NO1 in 2018. More in detail model and cost assumptions is explained in Appendix A.

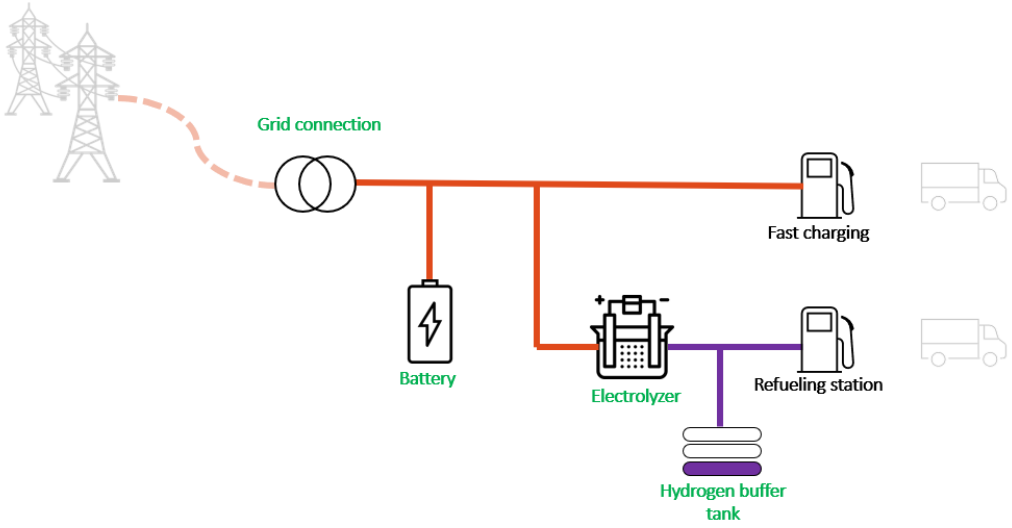


Figure 8 An illustration of the local system which is modelled. The sizes of components described in green text are optimized

As an attempt to mimic real world conditions, the designed demand of a station is assumed to be achieved only after 5 years and at the beginning of the operation only approx. 50% of its designed demand is realized. One of the sensitivity analyses in this work explore consequences of an even slower increase in the demand. The normal and slow energy demand increase is shown in Figure 9.

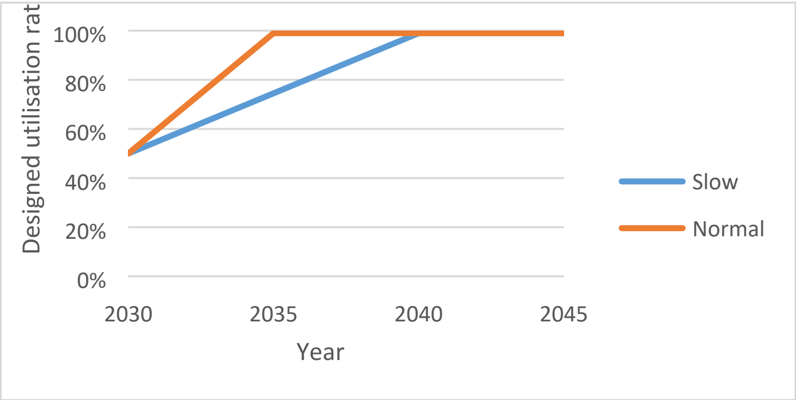


Figure 9 Demand increase for the modelled station over time

The result of the optimization is shown in Table 5 &Table 6 for H2+BEV and BEV only scenario. The sturdiness of the results has been studied through sensitivity analysis for one of the stations (Appendix A) and shows small impact of the station set-up.

The sizing of the equipment naturally corresponds to the annual energy demand and the increase of approx. 10 times can also be observed here from 2030 to 2050. For a hybrid station, hydrogen storage is used as a buffer, while in BEV only scenario batteries are used for energy storage. It is worth to notice that batteries have significantly smaller storage volume in comparison with hydrogen storage. Both the fact that batteries are a more expensive storage medium, as well as system cost benefits of enabling relatively constant operation of electrolyzer are important drivers for this result.

Table 5 The component sizing for different locations and years in H2+BEV scenario

		2030			2050		
		Hanestad	Otta	Gol	Hanestad	Otta	Gol
Electrolyzer	MW	3.8	4.2	2.3	58	54	22
H2 storage	MWh	68	77	51	1038	993	483
	ton	2.0	2.3	1.5	31	30	14
Battery	MWh	0	0	0	0	0	0
Grid connection	MW	6.2	7.7	4.6	114	101	59
Mean energy cost	NOK/kWh	1.3	1.2	1.2	1.2	1.2	1.1

Table 6 The component sizing for different locations and years in BEV only scenario

		2030			2050		
		Hanestad	Otta	Gol	Hanestad	Otta	Gol
Battery	MWh	0.6	1.5	1.9	7.9	18	13
Grid connection	MW	5.9	5.9	9.1	85	71	64
Mean energy cost	NOK/kWh	0.67	0.70	0.73	0.67	0.70	0.73

By both estimating peak hourly charging demand out from traffic count in Table 4 and in an optimized system including buffer batteries, which is presented in Table 6, it is possible to see how much the battery is helping to cut the annual demand peak. In Otta and Gol it is reduced by 12% and 9-10% respectively, while for Hanestad the reduction was by 22%. In absolute numbers it represents 0.8-1.9 MW in 2030 and increasing to 7-23 MW in 2050. The smallest battery is used in Hanestad at the same time it gives the largest reduction in grid connection, this dynamic of feasible battery size and its impact on grid reduction is assumed to be associated with how the hourly demand profile look like.

3.5 Hybrid hydrogen refuelling and charging stations

Within framework of the ITEM-project possible benefits with collocation of hydrogen refuelling and charging infrastructure considering also local PV-production was also investigated. The location of the analysis was also at the Oslo-Trondheim corridor. The results showed small differences in investment and energy costs, while it was easier to accommodate local PV production. In detailed description of the analysis is published as a scientific paper (in review) [47].

4 National analyses

The national analyses are as previously described done mainly with the two TØI-models NGM and BIG and with IFE-TIMES-Norway. This report focus on the part done by IFE-TIMES-Norway and a detailed description of TØI analyses are described in [6].

4.1 IFE-TIMES-Norway

4.1.1 General model description

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

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 industry, 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 heating demand in buildings is an energy service while the fuel used to heat the building is not. Each energy service demand category can be met by existing and new technologies using different energy carriers such as electricity, bio energy, district heating, 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 lifetime and learning curves.

Electricity, hydrogen, district heat and biofuels are examples of energy carriers being produced in IFE-TIMES-Norway, while fossil oil products and imported biofuels are examples of energy carriers that are produced outside the model and thereby having a fixed price.

IFE-TIMES-Norway needs exogenous input of electricity prices for countries with transmission capacity to Norway. In this project, the prices for the base year are the average prices from 2018, from NordPool [48] and Entso-e [49]. The future prices are a result from NVE, based on their analyses "Langsiktig Kraftmarkedsanalyse 2020 – 2040" [50].

Biomass can be used as raw material in the wood industry or as energy resources. A limitation of biomass is included as a base case in the model. The energy resources include use as chips/pellets in heating plants, conversion to biofuel or conversion to bio coal. Various bioenergy products can be produced from Norwegian raw materials or be imported. Norway has large biomass resources related to the forest and today approx. 22 TWh is annually felled. Some is exported and approx. 16 TWh is used in Norway now. In the model it is possible to increase the use of Norwegian forest resources to 31 TWh from 2030. A limitation of biogas is also added, 0.4 TWh in 2018-2020 increasing to 3 TWh in 2030. The production process of biogas is not included in the model yet.

Limitations of use of imported biofuel and bio coal are also included in the base case. From 2035, no import of biofuels or bio coal is possible, and in 2026-2035 the limitations are gradually increased.

A more detailed description of IFE-TIMES-Norway is available [51] and supplementary data are presented in Appendix B.

4.1.2 Modelling of transport

4.1.2.1 Structure

The road transport is divided into six different types: cars, vans, small trucks, large trucks driving <300 km/day, large trucks driving > 300 km/day and buses. Other transport than road transport is transport by rail, sea and air. In addition, a category gathering the rest of transport demand is included in "other transport". Demand is modelled as an energy demand (GWh/year) in these categories. This is not in focus of the ITEM project and further details are presented in the model documentation [51].

4.1.2.2 Demand

The transport demand towards 2050 is based upon the projections made in the national transport plan (NTP) 2022-2033 [52]. The demand projection is input from BIG (vehicles) and NGM (other transport modes). The total heavy freight transport is divided in the three truck classes of IFE-TIMES-Norway (25% small trucks, 37.5% large trucks small haulage and 37.5% large trucks long haulage in the base year). The division of data per geographical region and the relative development from 2018 to 2050 is based on county data of NTP 2022-2033. There is a shift from smaller to larger trucks, see Figure 10.

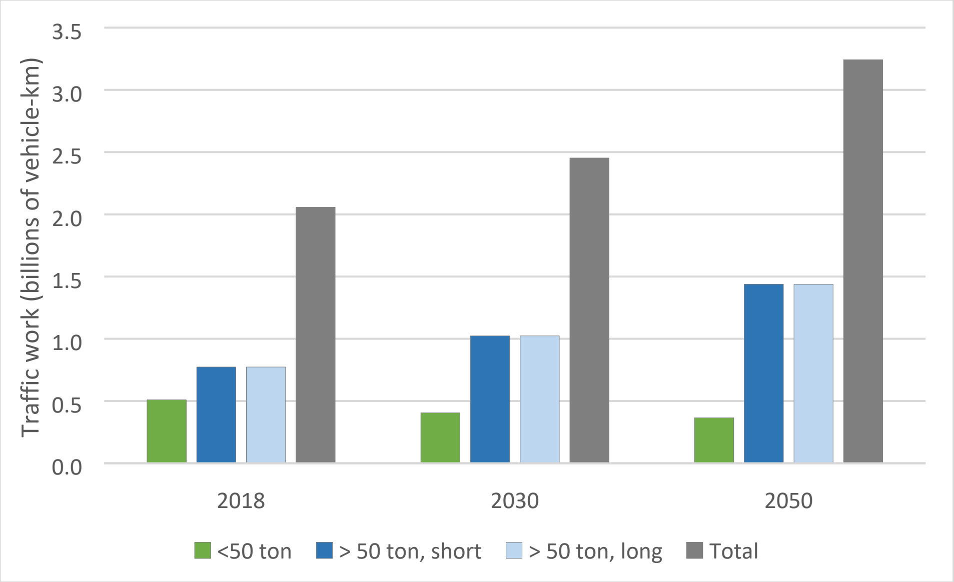


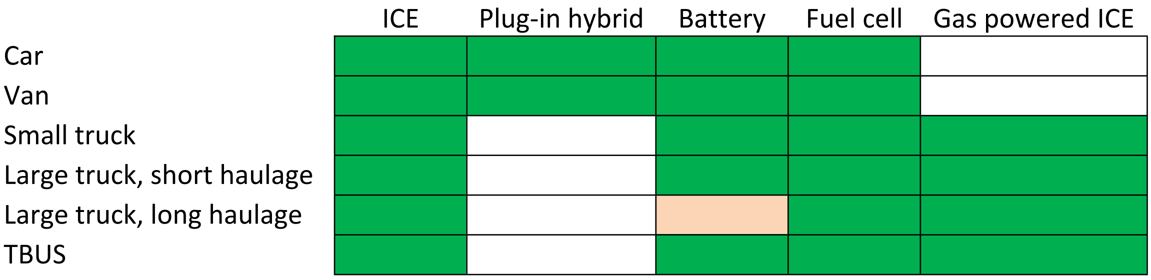
Figure 10 Development in demand of traffic work of three types of trucks, 2018-2050 (bill. vehicle-km / year)

4.1.2.3 Vehicles

Various technologies or powertrains can be used to satisfy the transport demand. The powertrains included in IFE-TIMES-Norway are internal combustion engine (ICE), plug-in hybrid with ICE, battery electric, fuel cell electric and gas-powered ICE.

Biofuels may be blended with petroleum diesel in ICE-technologies. The model has a minimum blending of 16% and the upper limit is increased to 100% by year 2040 (with a linear increase from 2020). Plug-in hybrid cars and vans are assumed to have a maximum share of 30% electricity.

When considering the specific conditions in the Norwegian transport sector and current technological development, not all the powertrains are considered of relevance for all the different demands. In Figure 11 an overview of which powertrains are considered for each type of road transport demand is presented. Battery powertrain is defined for large trucks with long haulage but is usually not included in reference scenarios as it is uncertain, per today, whether such a solution would be technically feasible.



	ICE	Plug-in hybrid	Battery	Fuel cell	Gas powered ICE
Car	🟩	🟩	🟩	🟩	⬜
Van	🟩	🟩	🟩	🟩	⬜
Small truck	🟩	⬜	🟩	🟩	🟩
Large truck, short haulage	🟩	⬜	🟩	🟩	🟩
Large truck, long haulage	🟩	⬜	🟧	🟩	🟩
TBUS	🟩	⬜	🟩	🟩	🟩

Figure 11 Matrix of powertrains applied for the different road transport demand

Battery vehicles are highly efficient with low maintenance and fuel costs compared to ICE vehicles. However, for heavy-duty applications their current limited range is a strong drawback and can oppose limits of their penetration in heavy-duty segments, but rapid technology increase is expected. A forecast to the trucks market share is shown in Table 7.

Table 7 Upper market share limitations of vans and buses

Technology	Market share		
	2018	**2030**	**2040**
Battery electric vans		15%	100%
Plug-in vans		15%	100%
Biogas busses		10%	50%
Battery electric Small truck	0%	100%	
Battery electric Large truck, short haulage	0%	100%	
Battery electric Large truck, long haulage	0%		

Further information on technology data of vehicles is presented in Appendix B and in IFE-report [51].

Optimalisation models (such as IFE-TIMES-Norway) can result in an unrealistically high implementation rate of new vehicles. A linking of the energy system model and the stock-fleet model is ongoing in order to make the implementation of new vehicles more credible. Thus, penetration rates from analyses with BIG can be used to calculate growth constraints for use in IFE-TIMES-Norway. This work is ongoing and will be presented in a separate paper.

4.1.2.4 Infrastructure battery charging

All electrical vehicles are depending on access to charging infrastructure, which brings an additional cost to the system in comparison with current well-established petrol filling station infrastructure. For private vehicles and vans three different chargers are included: Residential, Commercial and Fast charging. The Commercial charging is defined as slow charging that it is done close to non-residential buildings to represent that the car is charged at work.

Heavy-duty BEV can use slow and fast charging. Both profiles are shown in Figure 12 and the share between slow and fast charging for each truck type is shown in Table 8. As the majority of trucks below total GVW of 50 ton drives short distances, they are assumed to mainly utilize slow chargers. Large trucks with short haulage (total GVW ≥50 ton & <300 km/day) are assumed to entirely depend on slow chargers. On the other hand, large trucks with long haulage (total GVW ≥50 ton & >300 km/day) are assumed to utilize equal level of slow and fast chargers.

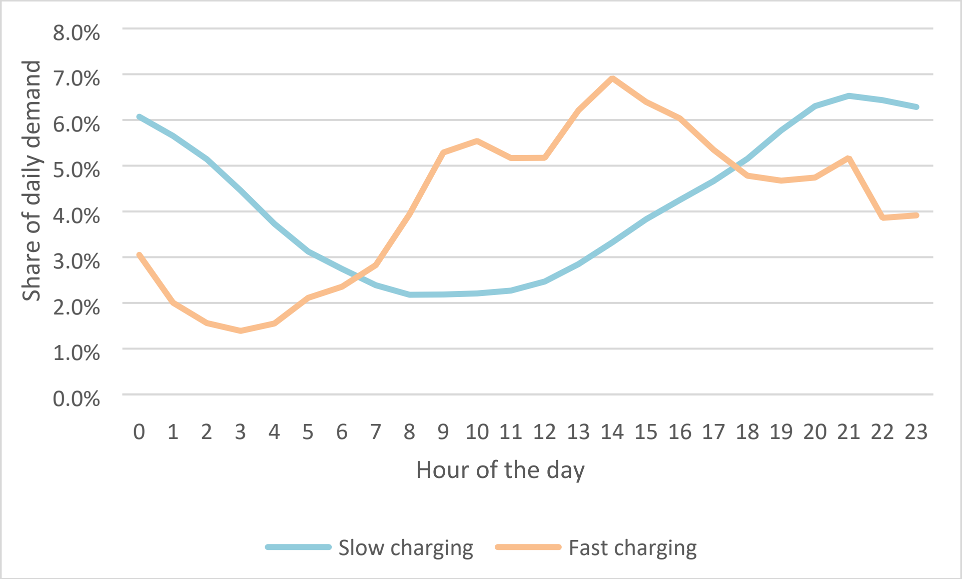


Figure 12 Slow and fast charging profiles based on data gathered within Limco project [53, 54]

Table 8 Share of energy supplied to electric trucks from slow and fast chargers

	Slow charging	Fast charging
Small trucks	75%	25%
Large trucks, short haulage	100%	
Large trucks, long haulage	50%	50%

More information about chargers (investment costs, efficiencies, capacities etc.) are available at [51].

4.1.2.5 Hydrogen production

Hydrogen from electrolyzers is assumed to be produced in each region either large scale (centralized) or small scale (distributed) and cost wise are represented by a 20 MW_{el} and 3 MW_{el} installed capacity, respectively. From centralized hydrogen production facilities hydrogen can be distributed to filling stations for a cost consisting of a truck service for distribution and hydrogen transport modules. The costs are provided both for alkaline and PEM electrolyzer and are build up from three parts: electrolyzer, compressor skid and other costs. The other costs cover engineering, control systems, interconnection, commissioning, and start-up costs.

Storage within a day is available both for hydrogen commodity at large scale production and for local hydrogen production for transport. On the other hand, seasonal storage is only enabled in connection to large scale production units.

Necessary infrastructure for filling hydrogen provides a cost in addition to hydrogen production and in certain studies it accounts for about half the total hydrogen cost for the customer. Costs for hydrogen refuelling stations (HRS) can vary greatly depending on size, pressure, degree of utilization and design.

4.2 Scenarios

4.2.1 Base scenarios

Two main scenarios are analysed, the “Slow decarbonization scenario” and the “Fast decarbonization scenario”. The “Slow” scenario is based on a technology driven market with an increase in CO2 taxes to 2000 NOK/ton CO2 in 2030 and a similar annual increase further on to 2050 is assumed, in line with the policies of today [55]. The present intention of the energy taxes for road transport is that the total taxes will not increase until 2030, by decreasing the road tax proportionally to increasing the CO2 tax, see Figure 14. The passenger cars purchase fees and taxes are maintained constant as per today. The “Fast” scenario includes fulfilment of EU-regulations on new vehicles and a CO2 tax increasing to 10 000 NOK/t CO2 in 2040, see Figure 14. An overview of the analyses is presented in Table B-1 in Appendix B.

A. Slow – present policies and CO2 tax
  - Constant tax rates until 2030 with
    - a CO2 tax of 590 NOK/ton CO2 in 2020 increasing to 2000 NOK/ton CO2 in 2030 and annual increase of 4% after 2030
    - decreasing road taxation

B. Fast – higher implementation of zero emission vehicles by more measures incl. higher CO2 tax
  - Increased taxes
    - CO2 tax increase to 10 000 NOK/ton CO2 in 2040
    - maintaining all other taxes at the same level as today
  - Achieve the targets in EU-regulation 2019/631 and 2019/1242. This is implemented in IFE-TIMES-Norway as a minimum of 15% new heavy-duty vehicles has to be ZEV in 2025 and 30% in 2030, and minimum of 45% of new vans from 2025 has to be ZEV.

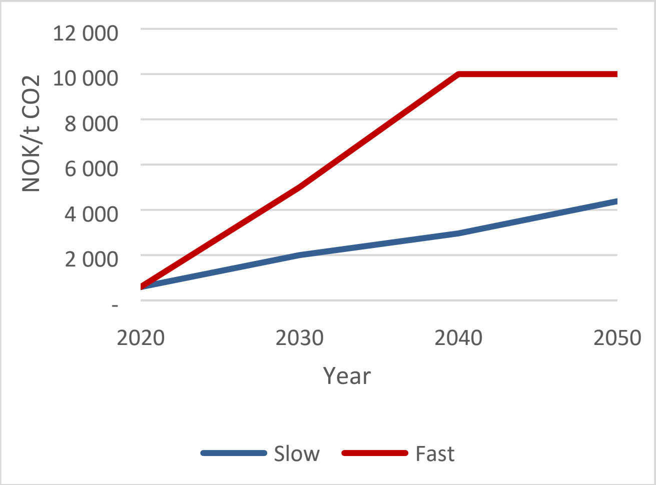


Figure 13 CO2 tax in the two scenarios “Slow” and “Fast”

Figure 14 Total diesel price for private cars in the two scenarios “Slow” and “Fast”

4.2.2 Alternative scenarios

Sensitivity analyses are made based on the two main pathways. Parameters that are analysed are:

- ZEV - Including/excluding the EU regulation of ZEV vans and trucks
- Unlimited use of biofuels instead of the base assumption of only Norwegian resources from 2035
- Unlimited use of biogas instead of the base assumption of only Norwegian resources from 2035
- VAT - Adding increasing VAT for cars and vans from 2023 to 2027 (reaching the general VAT of 25%)
- BEV - Removing limitation of battery electric vehicles for heavy trucks, long haulage, buses and some other transportation
- Demand - Decreased transport demand, no increase from today and increased industry demand
- Rate - Increased hurdle rate for investments in vehicles (10% instead of the general rate of 4%)

4.3 Results

The focus of the ITEM project and this report is heavy duty road transport and thus most of the results presented are related to heavy transport, although other results also are available. Impacts on the energy system is included, such as total electricity demand, electricity production trade and use of bio energy.

Heavy transport

Energy use for trucks will in all scenarios analysed decrease, as illustrated in Figure 15 for three main scenarios (Slow, Fast and Fast-BEV). This is due to improved energy efficiency of new vehicles, particularly battery electric vehicles (BEV). Figure 15 shows the end-use of energy and due to different efficiencies, this differs from the share of different types of truck, that is presented in Figure 16. The hydrogen uses in Figure 15 is the energy content of hydrogen, not the energy used for producing the hydrogen.

As earlier mentioned, the Fast scenario assumes that BEV cannot be used for long, heavy transportation, while Fast-BEV allows use of BEV also for the long, heavy transportation.

In the Slow scenario, fossil fuel will be a considerable share of energy use of trucks up to 2045 and even in 2050, some use of fossil fuels remains. Use of biofuel increases, blended in fossil fuels. The use of biogas increases and shows a maximum in 2030-2035 with 1.2 TWh/year. BEV is slowly introduced in 2023 and reach a high share from 2030 and forward. Hydrogen is introduced in 2045 and dominates in 2050. As shown in Figure 16, BEV becomes the dominant type of truck from 2035.

In the Fast scenario, hydrogen trucks are coming in use in 2035 and the use of hydrogen is 4.4 TWh in 2050. If this is produced be electrolysis, the electricity use will be 6.5 TWh. Electricity use for BEVs and production of hydrogen for trucks will be about 10 TWh in 2050. Use of fossil fuels will be low in 2035 and totally phased out from 2040 and forward. The total energy use, if hydrogen is produced by electrolysis, is almost the same as today.

If BEV can be used also for the long, heavy transports, total energy use is reduced by 4 TWh compared to today, due to the higher efficiency of BEVs.

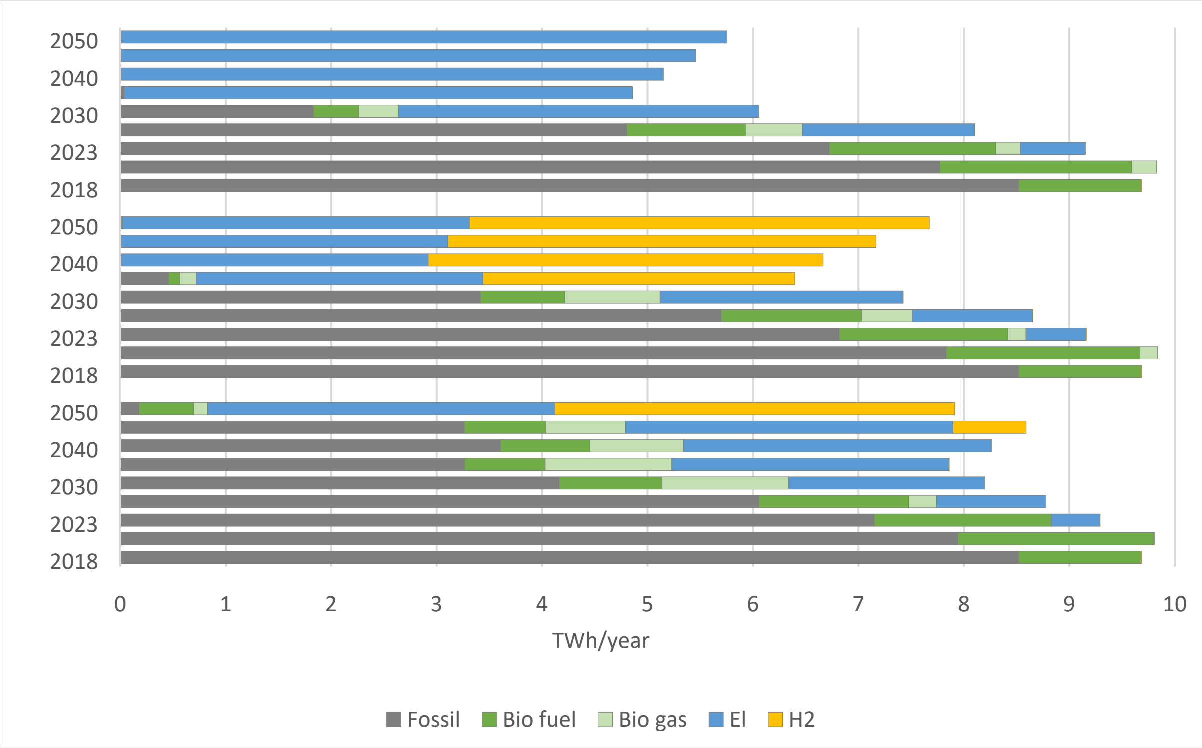


Figure 15 Energy for trucks by energy carrier for the scenarios Slow, Fast and Fast-BEV (TWh/year)

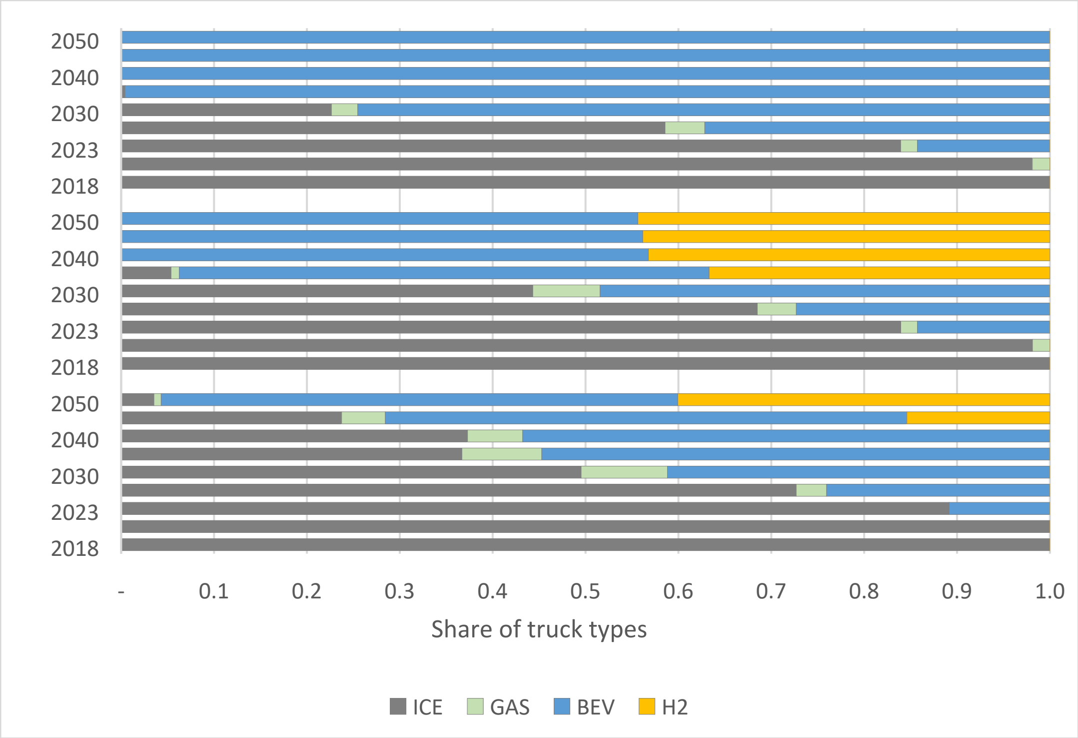


Figure 16 Share of different types of trucks for the scenarios Slow, Fast and Fast-BEV (billions of vehicle-km/year)

Figure 17 present results of different cases of the Slow scenario. If biofuels are not limited to Norwegian production from 2035, the use of BEV and hydrogen is delayed. Unlimited biogas resources in combination with unlimited biofuel resources results in more use of biogas trucks, mainly reducing use of ICE trucks, but also a small decrease in BEV. If only biogas is unlimited and all biofuels must be produced by Norwegian resources, then biogas trucks become more frequently used and ICE is significantly reduced.

Higher rate on vehicle investments has a similar impact as unlimited access to biofuels; it delays the introduction of ZEVs. The case with lower fossil prices shows a small impact with delayed use of hydrogen and slightly less biogas.

Figure 17 Share of types of trucks in different SLOW scenarios

Figure 18 present results of selected cases with the FAST scenario. Most impacts are similar to the Slow scenarios, as presented above. The possibility of using BEV also for long, heavy transportation, results in no use of hydrogen; only BEV is used from 2040. Several parameters in favour of hydrogen compared to BEV have been added to alternative cases of the BEV-scenario, but this do not result in replacement of BEV with hydrogen.

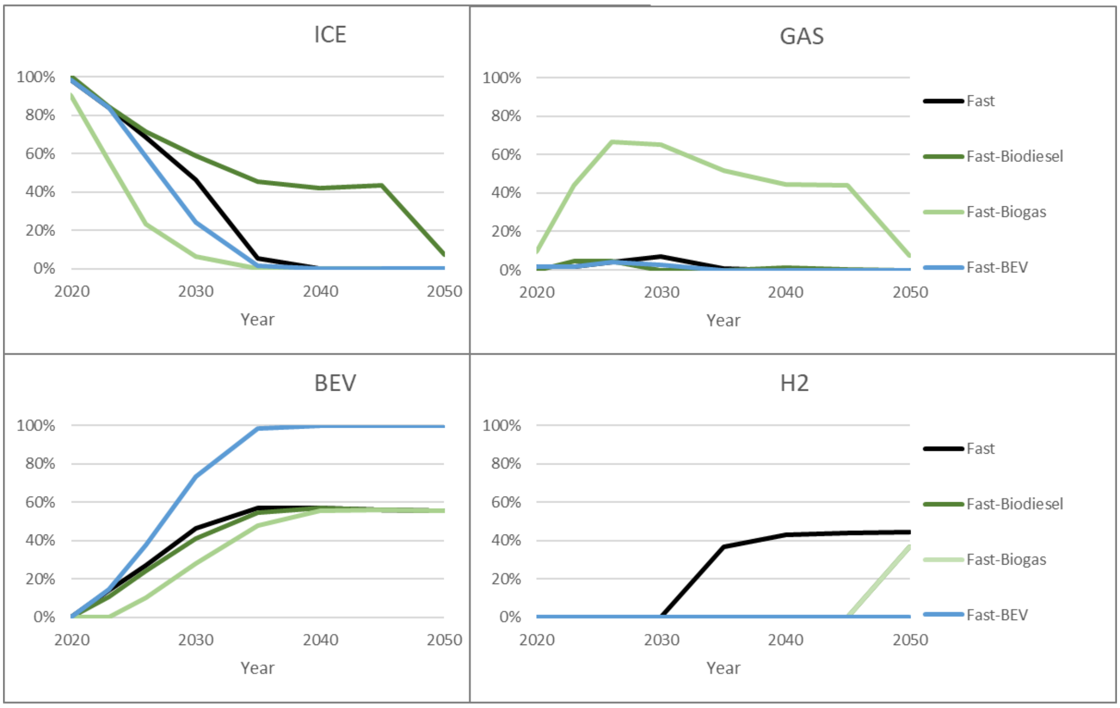


Figure 18 Share of types of trucks in different Fast scenarios

Hydrogen production

Hydrogen is mainly produced centrally and distributed by truck to energy stations. Only in NO4 hydrogen is produced by use of local electrolysers. Central production is by alkaline electrolysers while local production is by PEM.

The marginal hydrogen prices in the five market areas are shown for 2040 in Figure 19. The price shown is at the filling station, including all necessary transport and filling station equipment.

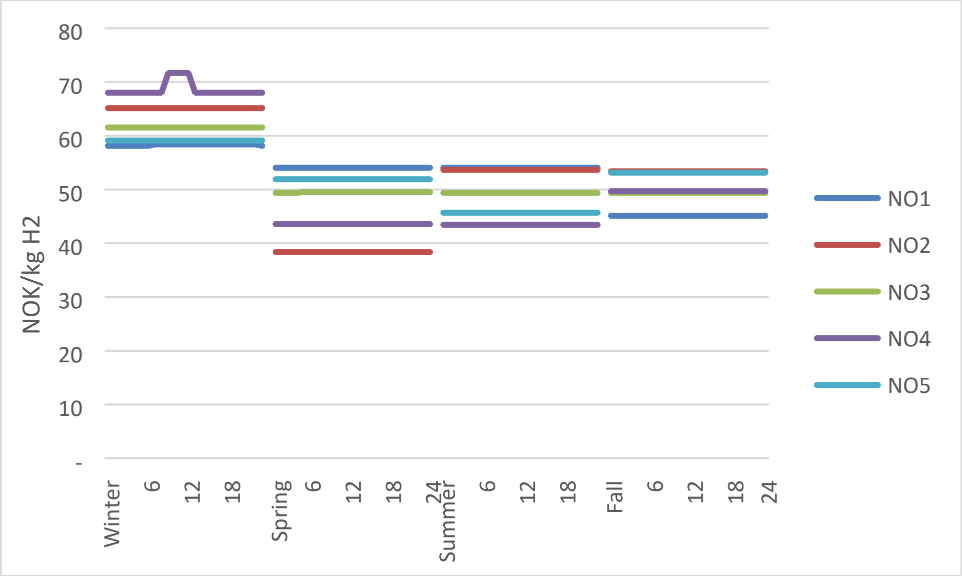


Figure 19 Marginal price of hydrogen at filling station in 2040 in the five regions (NOK/kg H2)

Power production and use

The power production is increasing in all scenarios by about 80 TWh in 2050 compared to 2018. An example of the power production is presented in Figure 20, for the Fast scenario. Hydro power is producing 150 TWh in 2050, wind power 46 TWh, PV 27 TWh and CHP less than 1 TWh. The difference between the scenarios is small, less than 2 TWh in most scenarios and about 3 TWh in the high demand scenario and the low fossil fuel prices scenario.

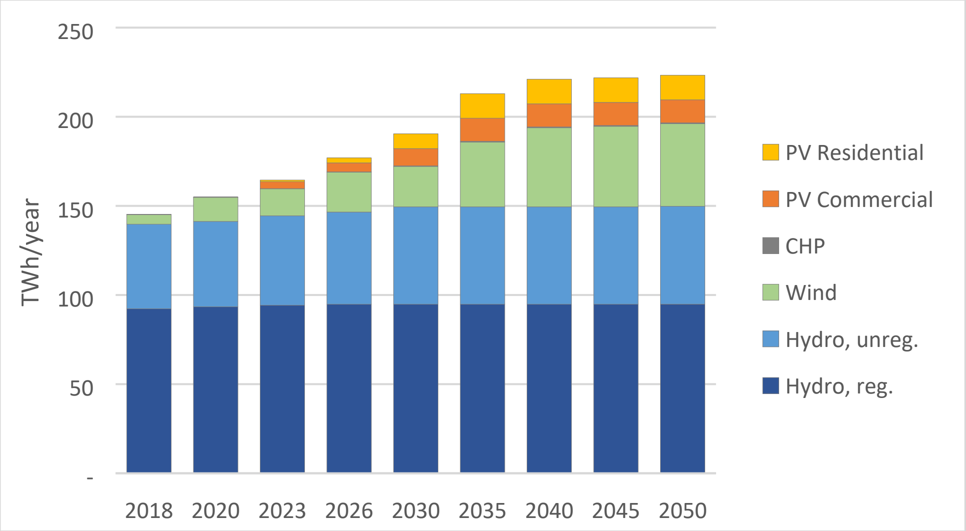


Figure 20 Power production in the Fast scenario, TWh/year

The electricity trade is also rather similar in the different scenarios, except for the scenario with high industry demand where trade is reduced by 16 TWh in 2030 and by 28 TWh in 2050, and for the scenario with zero growth in transport demand the net export is about 7 TWh higher in 2050 compared to base.

The use of electricity per sector is presented in Figure 21. Electricity use in buildings is rather constant at about 60 TWh/year. Industry demand is very uncertain; in Fast it increases by 14 TWh/year from 2020 to 2050, and in the high industry demand it increase by 46 TWh. With the possibility to use battery electric trucks also for long distances, the total use of electricity decreases due to the higher efficiency of BEV compared to hydrogen production by electrolyses.

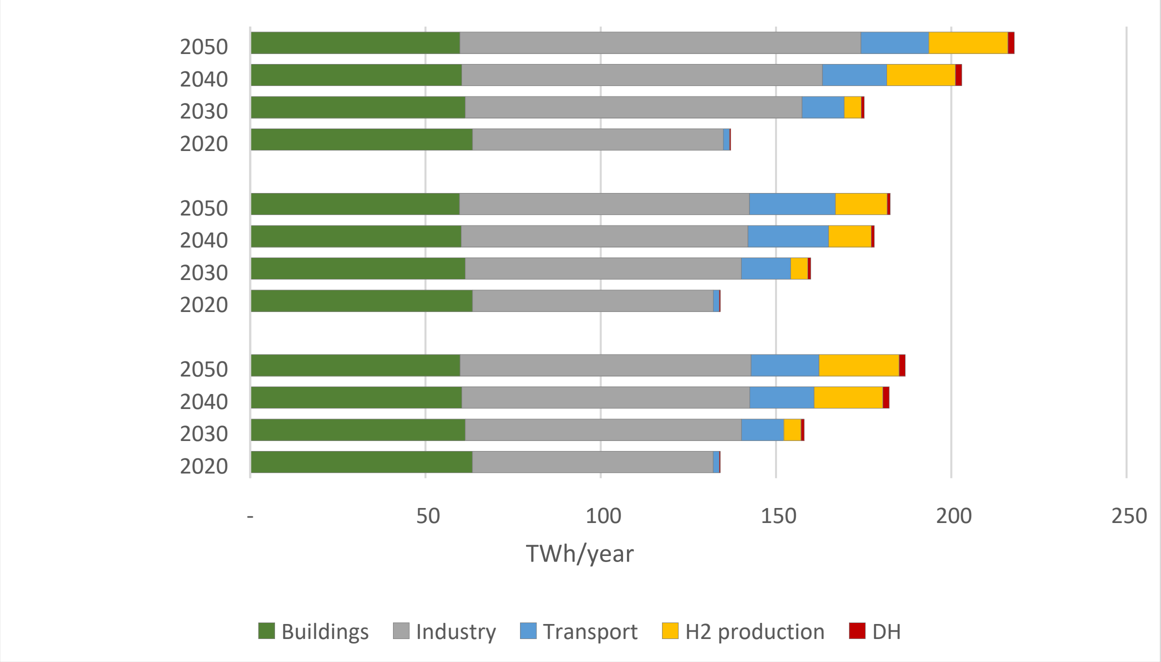


Figure 21 Electricity use in the Fast scenario and the alternatives with all BEV and with high industry demand, TWh/year

The load profile will be different if hydrogen is used for long distance trucks or if all trucks can be BEV. This is illustrated for price region NO1 in 2050 in Figure 22.

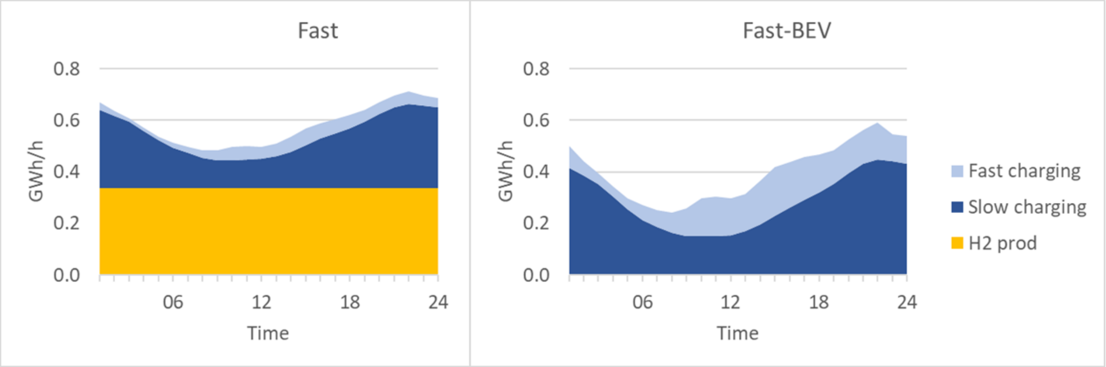


Figure 22 Load profiles in 2050, region NO1, for the Fast scenario and Fast-BEV, GWh/h

Bio energy

If biofuels can be imported unlimited with price of 1.8 NOK/kWh, no Norwegian bio diesel will be produced. The use of biodiesel is linked with the use of ICE since it is blended with fossil fuel. The same parameters increasing the use of ICE therefor also increase the production of Norwegian bio diesel (in scenarios with limited import of bio energy).

Until 2040, the Norwegian bio energy resources seems to be sufficient for the domestic need. In 2040 all Norwegian bio energy resources (annual growth) are used in the Fast scenario (but not in the Slow scenario), see Figure 23. The use of bio energy for heating purposes is reduced, while the production of bio coal for industry and bio diesel for transportation increase.

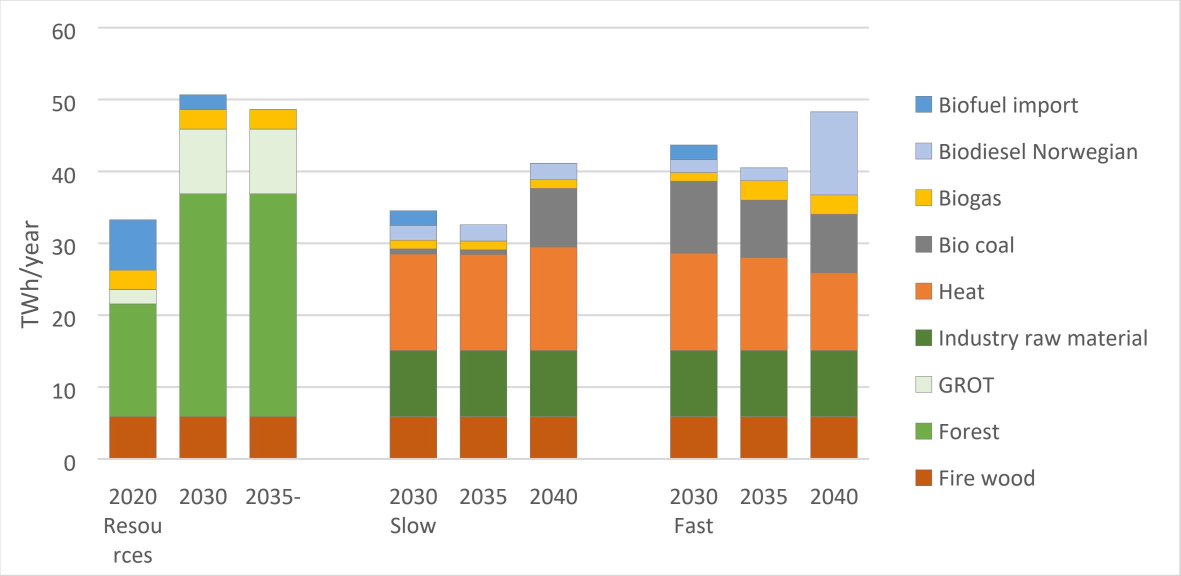


Figure 23 Bio energy resources to the left and use of bio energy in the Slow and Fast scenarios in 2030-2040 (TWh/year)

The use of biofuels in road transport is higher in 2030 than in 2050, see **Error! Reference source not found.**. In the Slow scenario, bio diesel is used when available, but in the Fast scenario biogas replaces some of the use of bio diesel. Biogas is mostly used by long distance, heavy trucks in 2030 and in 2050 these are replaced by hydrogen trucks.

CO2-emissions

The CO2-emissions from transportation decrease in all analysed scenarios, see Figure 24. To decrease emissions from transportation in line with the climate targets, it must be about 8 billion tons in 2030. In the Slow scenarios and the base case of the Fast scenario, this is only possible to achieve with an optimistic technology development and an optimized behaviour.

In the Slow scenario with unlimited access to biofuels, ICE trucks are used and the use of biodiesel and fossil diesel increase, and thereby also the emissions. In the Fast scenario with unlimited volumes of biofuels, the emissions are far below the target, indicating that both cheap biofuel and high CO2-costs are necessary if biofuels will be a possible solution.

Another possible way to reach the emission target is if BEVs can be used also for long distances heavy trucks. But this is hard to see with the short time left to 2030. Zero growth of transport demand is a possible way to reach the climate targets already in 2030, however this implies a need for societal changes which can be difficult to implement.

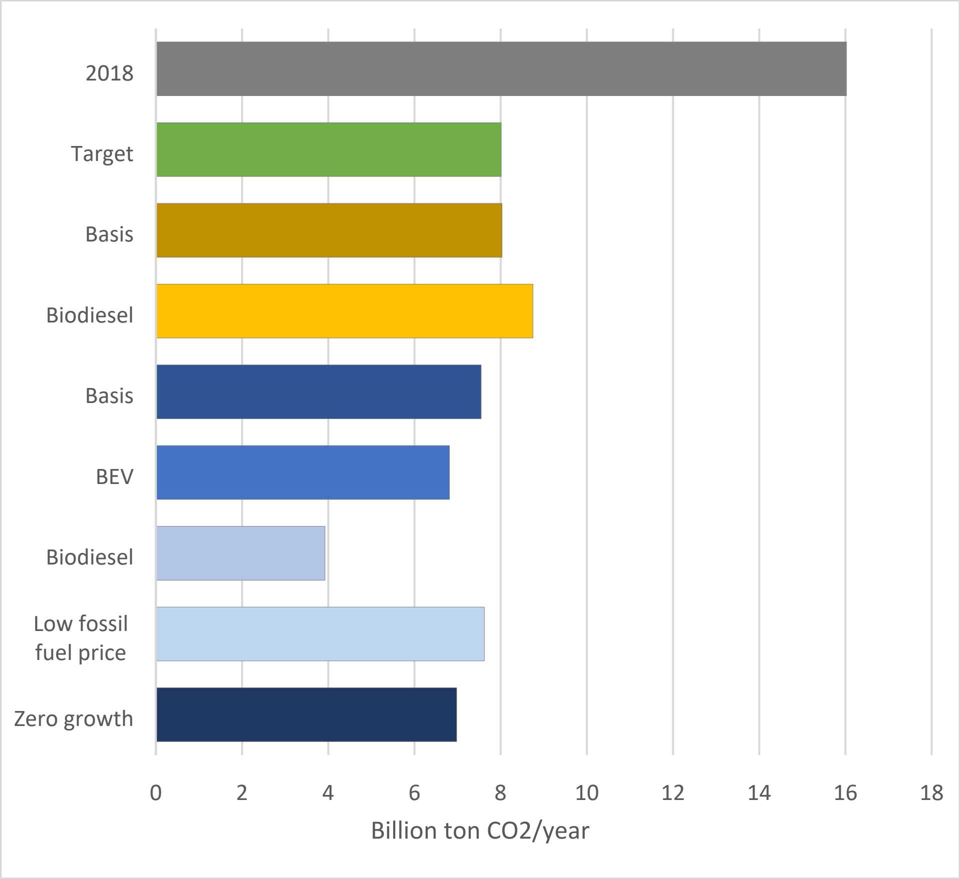


Figure 24 CO2 emissions from the transport sector in 2030 for selected scenarios, billion tons CO2/year

5 Conclusions and future work

5.1 Conclusions

The ITEM project has performed two different types of analysis: (i) an in-depth analysis of the two most important transport corridors in Norway: Oslo-Bergen and Oslo-Trondheim, and (ii) a national modelling framework integrating energy system models with improved vehicle, travel, and freight demand models. We have studied the energy use of heavy transport by use of a transport demand model, a fleet-stock model, a national energy system model and a local energy system model of energy stations. The results and conclusions discussed here are from the energy systems analysis on local and national level.

By linking a national energy system model such as IFE-TIMES-Norway with a local scale energy system model provides opportunity to model a specific component, such as a future energy station, in a more detailed way. By aggregating the result from the local model, the component can be presented more accurate in national model. In the case of an energy station, it provides insight related to system sizing including local flexibility such as local battery and hydrogen storage, peak demand and utilisation rate.

From the local scale analyses, and based on chosen methodology and assumptions, we observe that the energy demand for fast charging and refuelling in the corridors are in the range of 15-40 GWh in 2030 increasing to 160 to 450 GWh in 2050 in analysis with 100% zero-emission truck fleet. In H2+BEV scenario the energy demand is notably larger than in BEV only scenario, as direct electrification of the trucks is more energy efficient and because battery electric trucks are assumed to use depot charging extensively.

The grid would be exposed to 5-9 MW peak demand from a charging/refuelling station in 2030, which increases to 50-110 MW in 2050. The results are relatively similar for the BEV+H2 and the BEV only scenario. Similar peak demand, while lower energy demand, in the BEV only scenario implies that power demand from the grid will be much more volatile in the BEV only scenario.

With increased energy demand in the corridor, it is not obvious that the energy demand will be covered by one charging/filling station. It might become more feasible to distribute the demand on several smaller stations which might both offer better match for freight logistics as well as accommodate the energy demand better in the existing grid.

An important assumption in the local analysis was a flat intra-hour demand and the representativeness of chosen years of the traffic count, which together created the used demand profile. A flatter demand profile will improve the feasibility of an energy station and reduce its investment and operational costs. However, a great uncertainty is connected to the potential to flatten the demand, which would require a better coordination of the freight logistics which is directly connected to the aggregated result of the planning of many competing logistic companies.

At the national level, we have analyzed the impacts of zero emission heavy-duty transport on the energy system and future CO2 emission from the transport sector under different scenario assumptions with respect to technology development, future CO2 prices, transport demand etc. The main scenarios we have analyzed are:

1. **Slow** with present energy and climate policies
2. **Fast** with higher CO2 tax and stronger energy and climate policy measures

While the energy use for trucks decrease, due to improved energy efficiency of new vehicles, particularly battery electric vehicles, the demand for electricity and hydrogen will increase. Electricity demand in transport increases from present level at 2 TWh to 19 TWh in 2050 in the Fast scenario (all transport modes). In the Slow scenario the implementation of ZE trucks is slower, and there is still a share of conventional vehicles (ICE) in 2050. This is in line with other analyses made of transport sector in Norway [39-41].

The use of electricity for hydrogen production is in our analyses 20 TWh in 2040 and 23 TWh in 2050 in the Fast scenario. Compared to other studies, this is higher (NVE 7 TWh in 2040 and Statnett 15 TWh in 2050), but a large amount is used in maritime transportation and the uncertainty is high.

Decarbonization of transportation may also be achieved by use of biofuels incl. biogas. In our analysis we have assumed that Norway must be self-sufficient in the future and if only the annual growth of biomass is used (in addition to Norwegian biogas), the resources are not enough to decarbonize the transport sector considering also the biomass demand in industry and for heating.

It is noteworthy that hydrogen is chosen only in cases when battery electric trucks are not available as a competing technology, as both lower energy price and significantly higher efficiency are strong advantages for battery electric trucks. The analysis of local fast-charging station shows neither any barriers when considering power demand in comparison with a station serving both battery and hydrogen trucks, while refuelling costs are lower in a battery truck only scenario. For hydrogen trucks to be able to compete directly with BEV, we need faster technology development in hydrogen, financial support for hydrogen technologies or other policy measures in place to get use of hydrogen in road transport.

The technological feasibility of battery trucks serving the long-haul truck segment has been outside the scope of this project. Previous studies have shown a spectrum of both shortcomings of battery usage in this segment as well as a possible potential for it, which make it hard to conclude probable future development. On the other hand, for trucks operating for shorter distances, the battery trucks have an efficiency, maturity and cost advance over hydrogen, due to which it is reasonable to expect the domination of this technology.

Through our work we did not achieve a clear consensus on which technology might become the most feasible in long term for long-haul trucks, especially when considering the competition of national bio-resources with industry and other transport segments. It makes hydrogen still a possible candidate for the long-haul freight. However, with low maturity level and prohibitively high costs in the short term, this technology should be explored in line with battery-electric vehicles and biofuel/biogas solutions.

Almost 60% of daily trips in Norway is less than 300 km, thus a significant share of the trucks can be electrified with series produced battery trucks within near future. When considering that truck operators take economically rational choices the transition might happen rapidly if the right framework conditions are present.

As battery electric vehicles are expected to be charging to large extent at depots, policies should facilitate efficient charging of trucks there. This can be done by support grid upgrades and charger installations for depot as well as for complementary fast charging. Research focus is also important on how this charging can be integrated efficiently both in the grid and the logistic puzzle. As both grid investments and research activities have long lead times, they should be high up on the policy agenda of today.

5.2 Further work

The research related to linking the transport and energy models will be continued. The most important linkage will be through the introduction of growth constraints for implementation of new technologies (vehicles) derived from the vehicle stock model to be used in the national energy system model.

The modelling results show that we need continued technology development in battery and hydrogen technologies to be able to achieve our national climate targets. However, we will also need other policy measures such as continued investment support or other financial support measures to reach our targets, as well as measures targeting energy behaviour. Further work on implementing energy and climate policies in energy and transport models are needed to increase our knowledge in how technologies and people can contribute to the transition to low carbon transport sector.

In this analysis we have not included other societal barriers such as charging time, inconvenience for drivers, however we have assumed that the drivers adapt to the technology. We need more research on barriers and social aspects of the implementation of ZE trucks to understand if the drivers adapt to the vehicle technology, or the vehicle technology has to adapt to the drivers' habits and routines.

Hydrogen production has a strong economy of scale, which more probably will be reached faster in other transport segments than road freight due to the competition with battery electric trucks. To unlock the economy of scale of hydrogen production, the test ground and future roll out of hydrogen truck should be seen in relationship to green and blue hydrogen production for other demands in for example harbours or industry clusters. Further work related to analysis of how hydrogen technologies can be adopted in transport and industry is needed.

In the modelling of demand in the transport corridors the station size and component dimension are sensitive to both the demand profile and the total demand. In this work a series of assumptions was made on how the hourly distribution of vehicles and their demand would look like. Aspects like possible variations of the demand within an hour could help to improve the quality of the existing analysis as well as a more precise inclusion in the demand profile of trucks shorter than 16 m. These trucks have probably a distinct driving pattern at the same time as they are used more frequently for short trips, which make it hard to estimate their impact on current results.

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Appendix A – Supplementary information on local system

The additional material presented in the appendix over local systems contains of three parts. In the first part is presented graphs which gives a complementary information about the dataset from the Norwegian Freight Model (NMG) used in the analysis. In the second part is presented the tecno-economic parameters used for modelling the local energy system and last is shown results from a sensitivity analysis of the model.

Data from NGM

The NGM is a national model used to understand and predict freight streams on a national level and it has only been used in limited extent for understanding local freight flows, as in this analysis. As a quality assurance measure the model results from 2018 were compared to the closest complete traffic count set. It showed that the NGM estimates many more trips, than can be observed with the traffic counts, see Figure A-1.

To adjust the estimated trips in the future, an adjustment factor was identified by assuming that a more correct estimate of trucks passing chosen locations consists of all the vehicles longer than 16 m and 75% of the vehicles between 7,6 and 16 m. This estimation of actual trucks passing is shown as estimated volume in the Figure A-1. All data from NGM is adjusted in the analysis presented in this report according to the difference identified between data from NGM and estimations of actual trucks passing in 2018.

The mismatch could have various causes, for example that more freight is assigned to road transport relative to sea and rail, that in reality larger truck is used which can transport more goods per vehicle or that they are loaded more than assumed in the model.

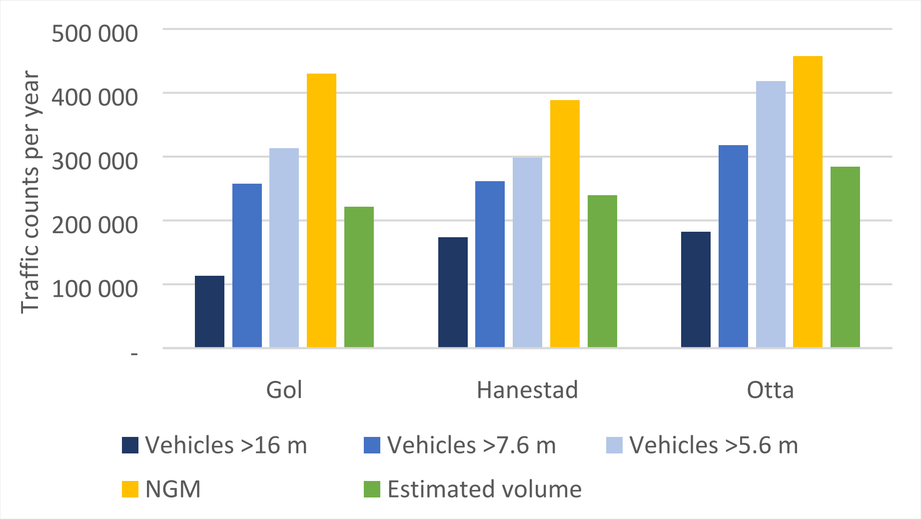

Figure A-1 Comparison NGM and traffic counts for 2018

In Figure A-2 is presented how the traffic volume is forecasted to increase in 2030 and 2050 for vehicles passing chosen locations as well as at the national level based on the forecasts used in the National Transport Plan (NTP) for 2022 – 2033. The trend of locations is expected to have similar growth to the national level, with a stronger increase for vehicles passing Hanestad and Gol by 2050.

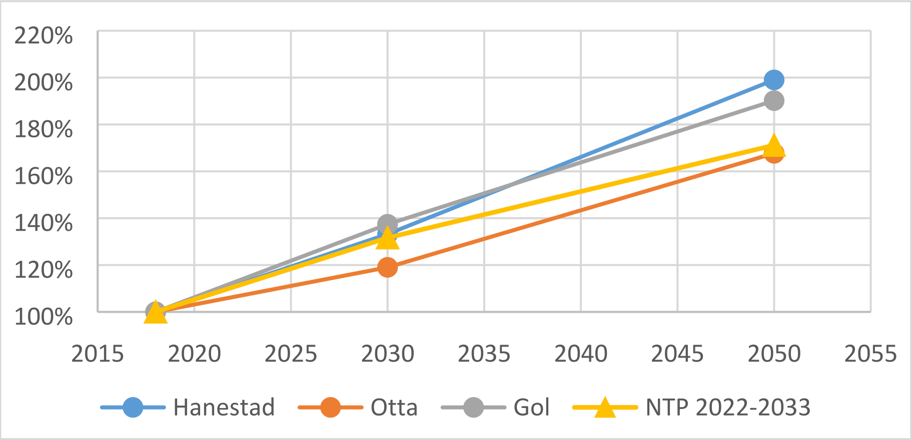

Figure A-2 Forecasted increase in vehicle km for trucks passing selected locations and national forecast

The Figure A-3 shows more details about the information available by using the NGM model and illustrates how each location is unique considering the composition of trip length and share of international trips. These conditions are relevant to understand the suitability and sizing of a future charging or hydrogen refueling infrastructure.

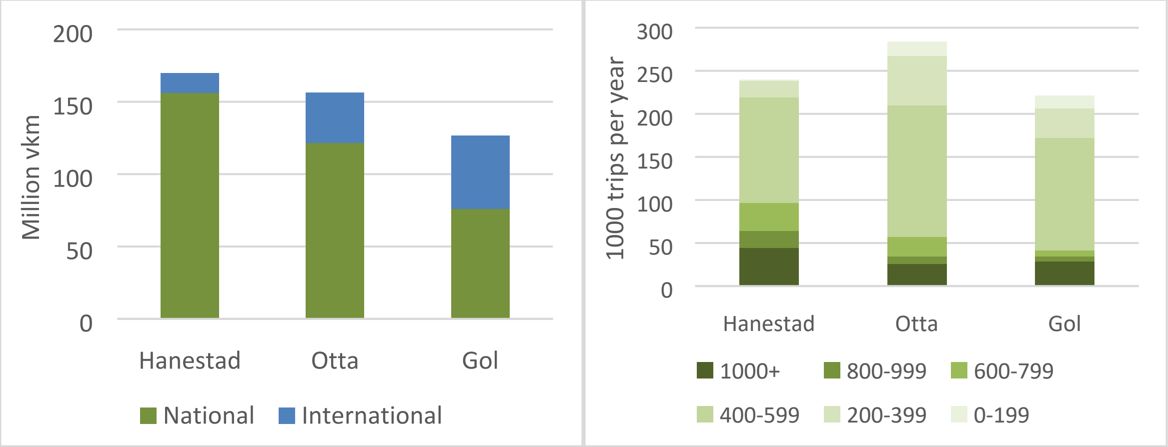

Figure A-3 Shows more details about the trips passing the selected locations in 2018 based on NGM model. The left graph shows total vehicle km for all the vehicles passing selected locations separated by national and international trips. The right graph shows the trips passing the location sorted by trip length.

Model assumptions of optimization model

A local model with hourly temporal resolution was set up in the TIMES framework and solved with CPLEX solver. TIMES has been developed to optimize regional up to global energy systems over a long time horizon. To enable such optimization, the temporal space has been limited to representative timeslices within a year and several years are aggregated to a single representative year. To model a local energy system with high hourly resolution, the timeslices were increased to 24 hours in 12 months consisting of 30 days, which gives 8640 hours in a year. It is marginally less than actual 8760 hours in a normal year. As the years in the local model are identical except increasing demand for the first five years, they are bundled to 3 years periods except the first and last year which are not bundled and the second and third year which consists of a single 2-year period.

The power prices are based on the spot price in NO1 in 2018, which on year average was on 419 NOK/MWh.

Grid fees were modelled in detail and are representing the fees charged by the distribution grid operator Elvia in 2021. As they are based on the highest power outtake and the model has only an hourly resolution it is assumed that the peak power outtake is 50% higher than the hourly average.

The main input parameters in addition to power price and grid fees are shown in Table A-1. Hydrogen dispensing is a relatively complex process with limited access to CAPEX and OPEX costs, tecno-economic analysis of such installation usually is presented in form of cost per energy unit refuelled. Therefore, also in this work such value was used. For more detailed description of chosen value can be found in the documentation of IFE-TIMES- Norway [51]. The cost corresponds to 24 NOK/kg$_{H2}$.

The charger is assumed to have significant variation within an hour, thereby it is assumed to have an hourly capacity factor of 50%, which is similar to how the grid fees are adjusted.

Table A-1 Main input data used in the model

	Efficiency	**Investment cost**	**Lifetime**	**Delivery cost***	**Hourly capacity factor**	**Annual maintenance cost**	**Charge/discharge cycles during lifetime**
	%	NOK/kW	years	NOK/kWh		NOK/ (year & kW)	#
	2030	2030	2030	2030	2030	2030	2030
Charger	0,9	3400	20		50 %		
Hydrogen dispenser			20	0,72			
PEM electrolyzer and compressor (350 bar)	0,64	18115	9			480	
Battery	0,95	4200 (NOK/kWh)	16				4500
Hydrogen storage		195,02	30				
Grid connection		2000	100				

Sensitivity analysis

To identify the most important design parameters and the rigorously of the models results, a sensitivity analysis was performed based on the scenarios listed and explained in Table A-2. Due to the model and demand similarity of the three chosen locations, the sensitivity analysis was only made for Otta.

Table A-2 Variation of the different parameters in the sensitivity analysis.

Scenario	**Description**
High grid connection fee	5 times higher (10 000 NOK/kW)
Power price - high	The power price is doubled
Power price - volatile	Average power price kept constant, while variability is increased
Demand - slow growth	Designed demand is reached only after 10 years of operation
Demand – volatile	A more volatile demand based on light duty vehicles traffic counts.

In Figure A-4 is illustrated the different power prices for the second half of the year, where the different power prices are easier to distinct. The high power price is always the double of the reference power price, while the volatile power price exponentially increase the deviation from the annual average price.

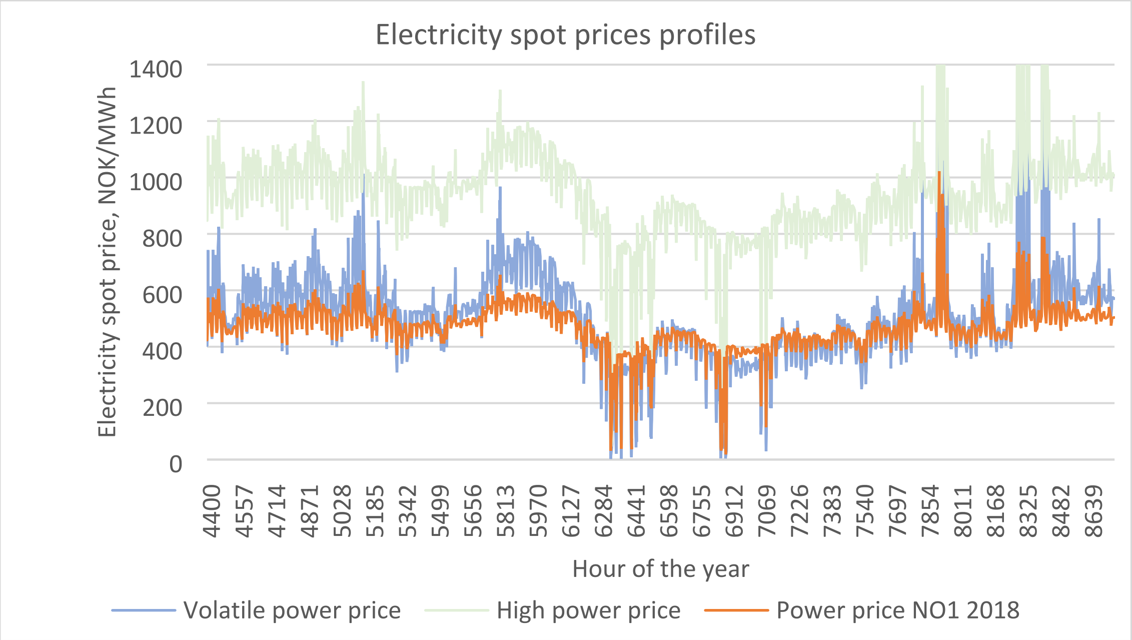

Figure A-4 Variation of the power prices for the second half of the period.

In Figure A-5 is shown the variation of the total traffic volume for passenger vehicles and trucks with trailer. The trucks have a relatively constant volume, while passenger vehicles have a large variation with a noticeable peak during summer. A constant volume of traffic counts can be translated to a constant demand for a future energy station. This impact of a more volatile demand, such as for light duty vehicles, where explored in the sensitivity scenario "Demand – volatile".

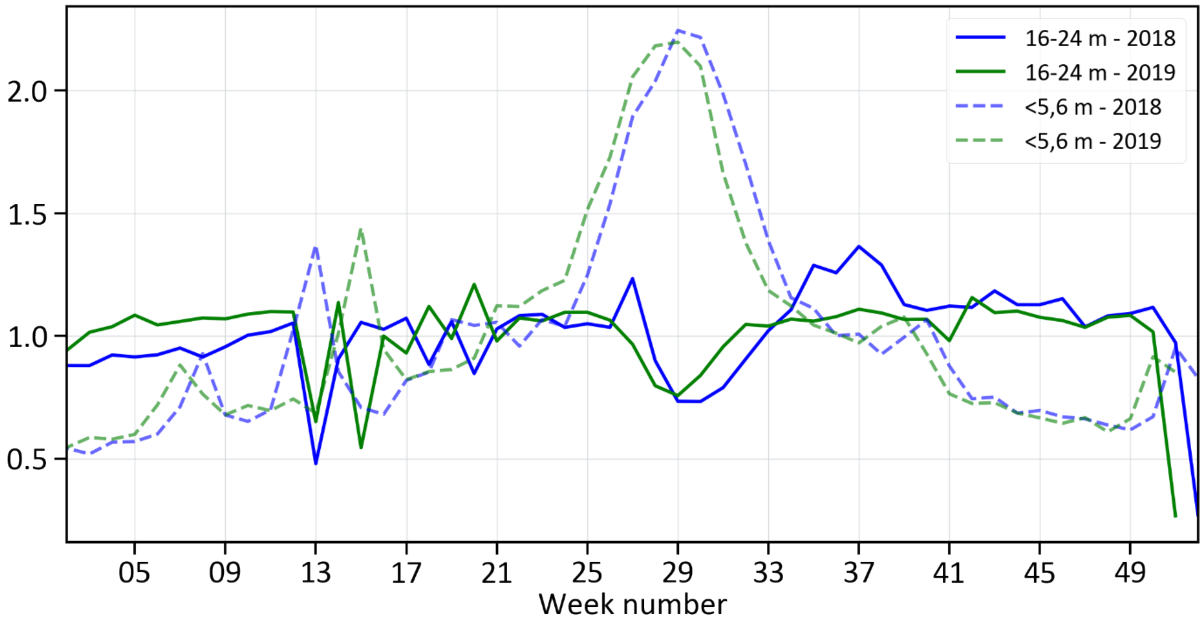

Figure A-5 Normalized weekly counts relative to yearly average at Otta

In Table A-3 and Table A-4 are shown how much the result in the sensitivity scenarios deviate from the results with the default value for the H2+BEV and BEV scenario respectively. The difference is also highlighted with color coding.

The results of sensitivity analysis for H2+BEV scenario shows relatively small changes in component size except when the demand profile becomes much more volatile throughout the year. To accommodate this increased variation all the components in the system is increased. It effects strongly the price per energy unit delivered, but not as much as the doubling of the power prices.

The sensitivity analysis for the BEV only scenario shows larger variation in component sizing and energy costs throughout the different scenarios. The similarity with the H2+BEV scenario is that high power prices and volatile demand give the highest increase in cost of energy delivered. A distinction from the H2+BEV scenario is that the flexibility element is decreased when the demand becomes more volatile. A possible explanation could be that the monthly and annual peak, which induces grid and grid connection fees, occurs more seldomly with the volatile demand profile and as peak shaving is batteries main value creation source, it becomes less profitable. That is though not the case in the H2+BEV scenario where the flexibility asset in form of hydrogen storage is increasing the most. This result might be based that the hydrogen storage is offsetting both the investment costs in the grid and the electrolyzer, which makes it relatively more feasible option compared to pure capacity expansion.

Table A-3 Result of the sensitivity analysis for the H2+BEV scenario

	Default	High grid connect fee	Power price - high	Power price - volatile	Demand - slow growth	Demand - volatile
Electrolyzer	100%	101%	100%	100%	85%	187%
H2 storage	100%	101%	101%	101%	100%	213%
Grid connection	100%	97%	100%	100%	99%	194%
Energy cost	100%	105%	138%	109%	100%	120%

Table A-4 Result of the sensitivity analysis for the BEV Only scenario

	Default	High grid connect fee	Power price - high	Power price - volatile	Demand - slow growth	Demand - volatile
Battery size	100 %	144 %	152 %	117 %	85 %	54 %
Grid connection	100 %	89 %	88 %	96 %	104 %	233 %
Energy cost	100 %	113 %	158 %	100 %	103 %	130 %

Appendix B Supplementary information on national analyses

Input data

The transport demand towards 2050 is based upon the projections made in the national transport plan (NTP) 2022-2033 [52]. The relative change in transport service demand is presented in Figure B-1.

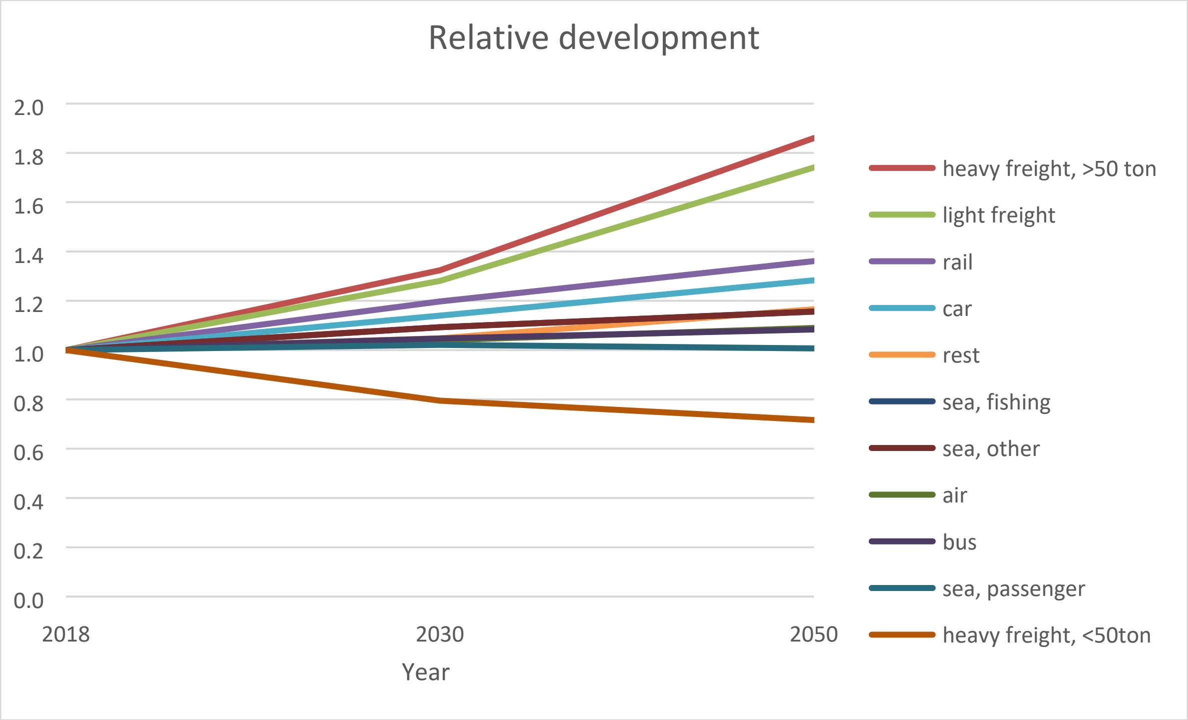

Figure B-1 The relative change of transport demand in 2030 and 2050 compared to 2018

The sensitivity analyses carried out is presented in Table B-1.

Table B-1 Overview of analyzed cases

		Unlimited			
Analysis	**CO2 price in 2030**	**Bio diesel**	**Bio gas**	**BEV**	**Other**
Slow					
A1	2000	No	No	No	
A2	2000	No	No	No	EU demand ZEVs
A3a	2000	Yes	No	No	
A3b	2000	Yes	Yes	No	
A3c	2000	No	Yes	No	
A4	2000	No	No	No	VAT cars
A5	2000	No	No	No	Lower fossil prices
A6	2000	No	No	No	Higher rate for vehicles
Fast					
B1	5000	No	No	No	EU demand ZEVs
B2	5000	No	No	No	No EU demand ZEVs
B3a	5000	Yes	No	No	
B3b	5000	Yes	Yes	No	
B3c	5000	No	Yes	No	
B4a	5000	No	No	Yes	
B4b	5000	No	No	Yes	
B4c	5000	No	No	Yes	
B4d	5000	No	No	Yes	
B5	5000	No	No	No	Lower fossil prices
B6	5000	No	No	No	Higher rate for vehicles
B7	5000	No	No	No	No transport demand increase
B8	5000	No	No	No	High industry demand

Results

The different scenarios give the same results for investments in new passenger cars and the same use of energy as well. BEV is introduced fast and after 2035 fossil fuels are phased out. The development of vans is similar, but with slightly delayed BEVs, see Figure B-2.

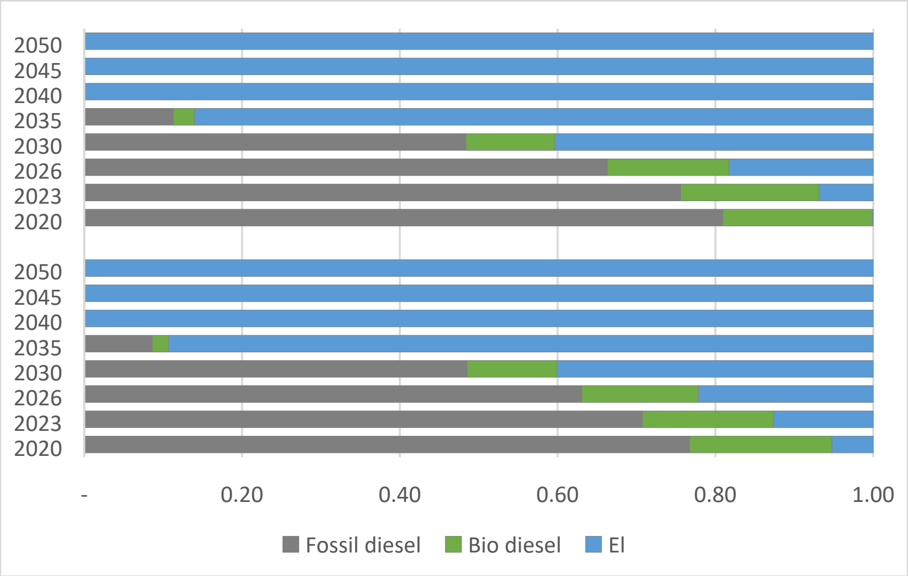

Figure B-2 Share of energy use in passenger cars and vans in the Slow scenario

The second largest transport sub-sector is sea transport. Fossil fuels are used longer, but also here the energy use becomes fossil free in 2050 in the Fast scenario, see Figure B-3. The transition is much slower with lower CO2 prices and use of biogas is then marginal.

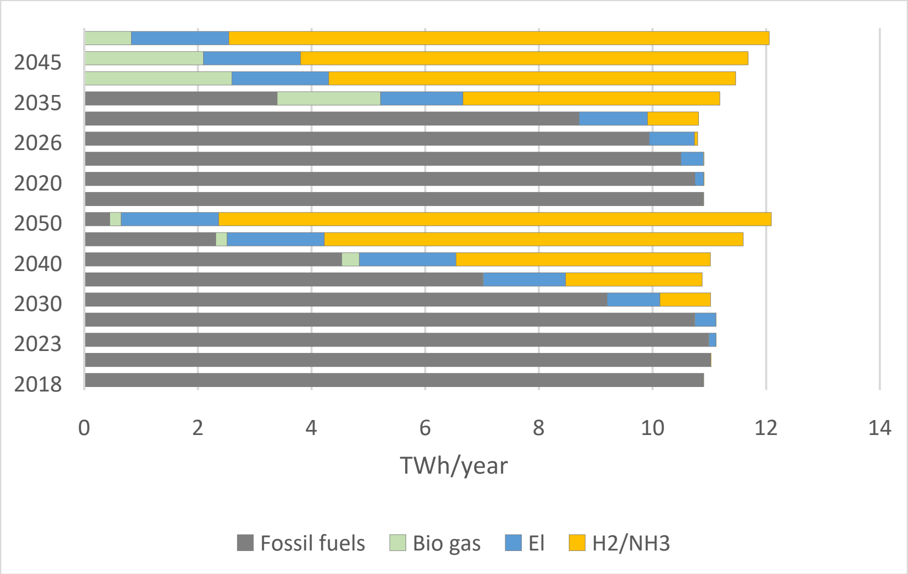

Figure B-3 Use of energy for sea transport in the Slow and Fast scenarios (TWh/year)

The use of biofuels in road transport is higher in 2030 than in 2050, see Figure B-4. In the Slow scenario, bio diesel is used when available, but in the Fast scenario biogas replaces some of the use of bio diesel. Biogas is mostly used by long distance, heavy trucks in 2030 and in 2050 these are replaced by hydrogen trucks.

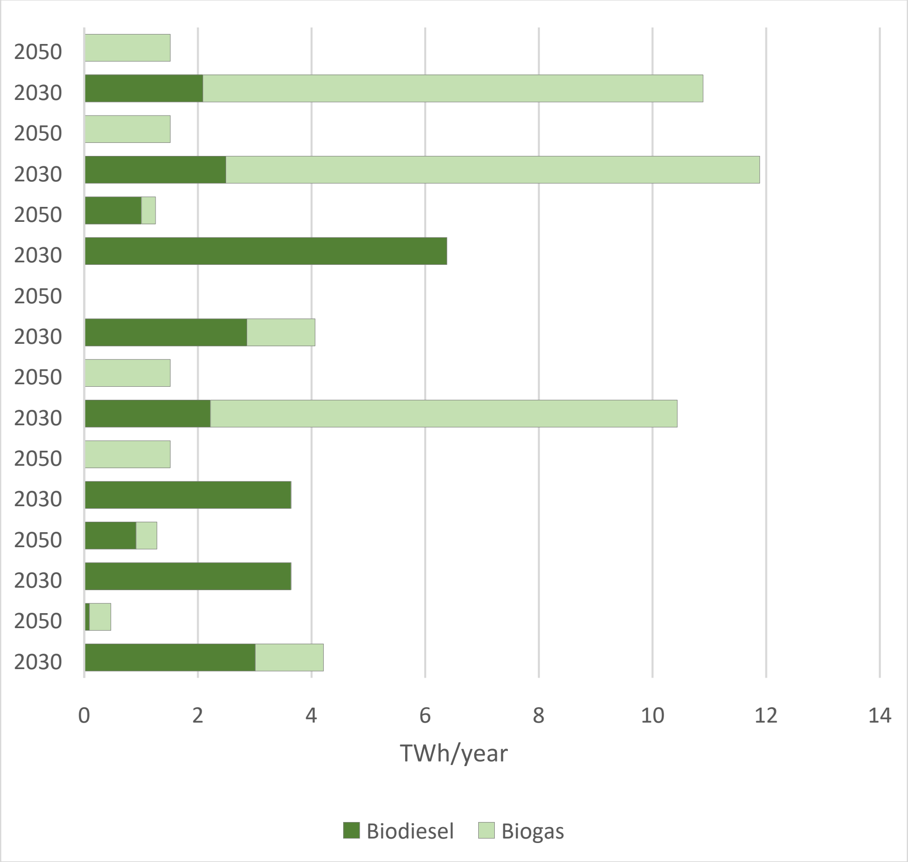

Figure B-4 Use of biofuels in road transport in 2030 and 2050 in the Slow and Fast scenarios with varying limitations on biofuels (TWh/year)

Biodiesel based on Norwegian wood products is produced in all scenarios, except those with unlimited availability to import biofuels. The production is low in Slow scenarios and increase considerable in Fast scenarios from 2040, see Figure B-5**Error! Reference source not found.**.

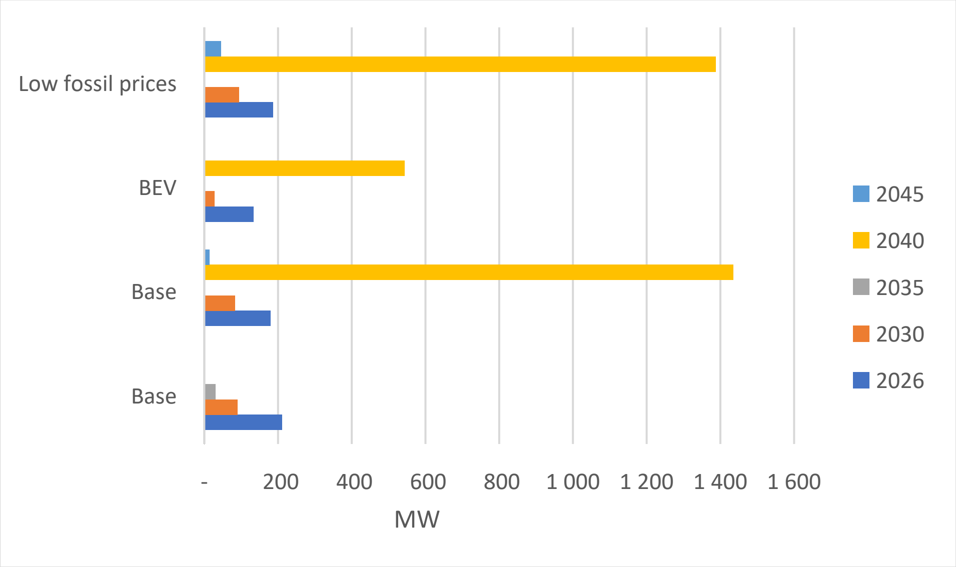

Figure B-5 Investments in new production capacities of Norwegian biodiesel production in a few representative scenarios (MW/year)

Tittel: Impact of zero emission heavy-duty transport on the energy system

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