Nordic Energy Outlooks - Final report WP4

Fossil-free and resource efficient transport

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Abbreviations

GAINS model = Greenhouse Gas and Air Pollution Interactions and Synergies Model

GHG = Greenhouse gases

highRES = The high spatial and temporal Resolution Electricity System model

IIASA = International Institute for Applied Systems Analysis

MTFR = Maximum Technical Feasible Reduction

MFR = Maximum Feasible Reduction

NDC = Nationally determined contribution under the Paris Agreement

NECP = National Energy and Climate Plan

NOx = Nitrogen oxides

NVDB = Nasjonal vegdatabank (National Road database)

ON-TIMES model = Open Nordic Integrated MARKALEFOM System Model

PM = Particulate Matter

WP = Work Package

1. Introduction

1.1. About the Nordic Energy Outlooks programme

Nordic Energy Outlooks [1] (NEO) is a programme organised by Nordic Energy Research, and financed jointly by Nordic Energy Research, the Swedish Energy Agency, the Research Council of Norway, and the Danish Energy Agency.

The main aim of the programme is to *Strengthen Nordic research competence and cooperation in the field of energy systems analysis, by building on existing national research programmes*. By creating a forum for collaboration between different research groups and institutions, NEO helps to synthesise the results of current national research and put these into a Nordic context, but also help to clarify how the choice of analytical methods can create different results.

An additional aim of the programme is to discuss if and how the results from the programme can be used for following up on the integrated national energy and climate plans (NECP), and if the results can provide a regional perspective. Figure 1-1 illustrates the aims of the program.

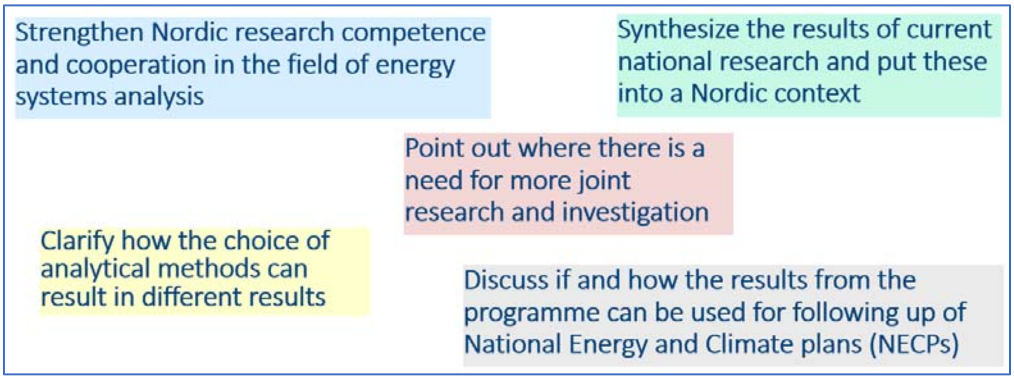

Figure 1-1: Aims of the Nordic Energy Outlooks programme

The programme is divided into four work packages (WPs), as shown in Figure 1-2, in addition to a separate WP for project lead. Each WP is carried out by selected research institutes in collaboration with SINTEF Energy – which is the project lead institution for the program. The outcomes from WP1, WP2 and WP3 are documented in [2]–[4], whereas the outcome from WP4 is documented in this report. The research organisations included in WP4 are Danish Energy Agency (DEA), the Institute for Energy Technology (IFE), IVL Swedish Environmental Research Institute (IVL), SINTEF, and University of Oslo (UiO) (see descriptions in Section 1.4).

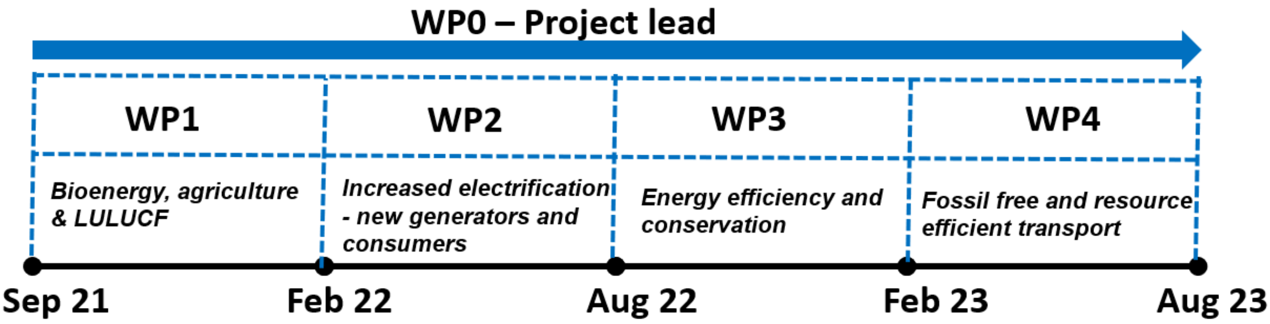

Figure 1-2: Overall structure and timeline for Nordic Energy Outlooks

1.2. WP4: Fossil-free and resource efficient transport

Transforming transport is a key energy challenge in the Nordic region to achieve the ambitious climate targets set by the Nordic governments. The Nordic stakeholders generally need a better understanding of how transport and energy systems interact with each other.

Several studies ([5], [6], [7]) have explored pathways towards meeting the goals for decarbonising the transport sector in the Nordic countries and they point towards a need for extensive changes in different parts of society. There are several strategies for reducing the GHG emissions in the transport sector including increased efficiency, reduced transport demand, and shifting to various fuels with low or zero GHG emissions. The impact of the different strategies for the Nordic transport sector on other environmental impacts such as emissions of air pollutions need to be assessed for policy makers, industry, and researchers to better understand the sustainability of different pathways. Increased knowledge is thus needed in terms of environmental impact of e.g., fuel switch, increased electrification, shared mobility, and consumer behaviour.

Electrification of vehicles (promoted as a key strategy in in several Nordic countries but primarily in Norway) helps to improve energy efficiency and reduces local air pollution (the latter is also true for the use of hydrogen). However, it takes time to transform the existing vehicle fleet (particularly when also considering ocean and air transport), both due to the long lifetime of vehicles and due to that it may be difficult to rapidly scale up battery production, and thus carbon-based transportation fuels may remain important in the coming decades (and have been promoted as key strategies in for example Sweden and Finland). By increasing the use of biofuels in parallel with electrification and energy efficiency improvements, one may achieve more rapid reductions in fossil fuel use in the transport sector. However, the impact on other emissions to air are not clearly known.

The transport sector in Norway is currently undergoing a transition to electric mobility. For the past decade, the growth in both electric car sales and charging infrastructure development has been world leading. In addition, electric drivetrains are introduced in other sectors such as urban buses, vans, taxis, ferries, and distribution trucks in an increasing pace. This has had an impact on the emissions from transport, mostly attributed to more than 0.5 million EVs in the Norwegian vehicle fleet. The emissions will be reduced even more if the political goals for 2025 (100% of new cars are EVs) and 2030 (e.g. 50% of new trucks are EVs) are met.

In addition to direct electrification and the use of biofuels, other emerging fuel production pathways could become potential options for reducing emissions in parts of the transport sector. Challenges arise in maritime and air transport, where long distances and carrying space limit the use of low-energy density solutions like batteries. Hydrogen could become a fuel replacement option in these segments, although new infrastructure and upgraded vehicle fleets would be required. Synthetic fuels could thus play a role as an alternative fuel supply option which could make use of the existing infrastructure and fleets [8]–[10]. For example, in the aviation sector, ongoing project developments aim to address some of these challenges by building new synthetic fuel production plants to cover the energy demands from domestic aviation in Norway [11], [12]. However, further understanding of the future role of emerging fuel options in hard-to-abate segments of transport – like aviation – is needed to get a perspective on the long-term decarbonisation potentials and overall impacts of these options.

Having committed to the Paris Agreement, Norway aims to reduce its greenhouse gas emissions by 90% to 95% within 2050 compared to the 1990 level [13]. Transport is the highest emitting sector in Norway making up 33% of total greenhouse gas emissions in 2021 [14]. Of this again about 54% comes from the road traffic. It is clear from this that for Norway to reach it greenhouse gas emission reduction targets it is essential with a decarbonisation of the transport sector. As mentioned, a means to achieve this Norway targets that all new cars sold in 2025 and after should be zero-emission vehicles [15]. Efforts like this does however cause an increasing demand for raw materials used in the energy transition. For instance a more than 12 and 16 times worldwide increase in lithium demand compared to current global supply in the e-mobility sector is forecasted for 2050 [16].

1.3. Research objectives and research questions

The overall goal of the assessment made by IVL in this project is to contribute to increased knowledge and understanding of the environmental effects of different decarbonisation strategies for the Nordic transport to better understand the sustainability of different pathways. By developing and applying tools that integrate the decarbonisation potential and impact on emissions of air pollution of different measures in the transport sector, we aim to inform smarter Nordic transport and energy policy. More specifically, we aim to inform Nordic policy makers as well as Nordic energy system analysts and about the potential importance of addressing air pollutants in climate policies and assessments in addition to GHG emissions. The assessment in this study provides an example of how it can be done (focusing on Sweden, Norway, and Denmark) and illustrates some initial assessments.

The main research objectives of IVL are connected to environmental effects of Nordic transport pathways towards climate neutrality:

- Scenarios for decarbonising the Nordic transport sector including varying levels of different key measures and options (e.g., electrification, biofuels, hydrogen, and transport demand).
- Development of a modelling tool for linking and transferring data between the Open Nordic TIMES model (ON-TIMES) model and the GAINS model.
- Assessment of the potential impact of different decarbonisation scenarios of the Nordic transport sectors on the most common emissions of air pollution including NOx and particulate matter.

The contribution of SINTEF to this project is to increase the understanding of how the potential impact of transport electrification on the energy system can be implemented in energy system analyses. This will be done by evaluating whether an introduction of a higher degree of details from domain-specific models will improve the results from an energy system model.

The main research objectives of SINTEF are connected to adaptation of methods for iterative modelling of transport and energy systems:

- Investigate how the increased electrification of transport can be implemented in energy system analysis.
- Investigate the need for an adaptation of models and methods from ongoing projects, with the aim of potentially implementing energy demand from transport in an energy system model for the Nordic countries.
- Investigate different scenarios and projections for electrification and development of transport, including an assessment of different time horizons, fuels, and demographic development.

The main research objectives of IFE are connected to emerging fuels and technology options in the aviation sector:

- Incorporate additional detail and options in the aviation sector for explorative analysis applying the low-carbon scenarios from the IFE-TIMES-Norway model.

- Assess the potential role of different sustainable aviation fuels as replacements for fossil-based options used in domestic aviation.
- Explore the potential of synthetic fuel pathways and carbon capture and utilisation to supply green aviation fuels.

The aim of the Danish Energy Agency in this project is to uncover opportunities for improving the approach to projecting energy consumption within the transportation sector, looking to the unique insights offered by deliberative democratic processes. The main research objectives are:

- Examine the characteristics of the foundational assumptions underpinning the Danish Energy Agency's projection of future Danish energy consumption within the transportation sector.
- Explore how the above-mentioned assumptions compare to recommendations on transportation emerging from two distinct cases of deliberative democratic processes.

The aim of the contributions from UiO in this report is twofold. Firstly, due to the rising deployment of batteries and renewable energy technologies, many of which depend on critical raw materials, it is essential to incorporate this supply risk into energy system models to ensure that they provide system designs which shows resilience against these risks and help ensure the feasibility of the transition to net-zero energy systems. In addition to this, the increased demand from electric transport makes it essential to incorporate this into electricity system models. To increase the knowledge on the topic, this work includes efforts to improve the spatiotemporal distribution of electricity demand from electric transport and the effect this has on energy system model results.

The main research objectives of UiO are connected to sustainable batteries in mobility and critical materials:

- How does the Nordic future net-zero energy system design change when explicitly representing socio-environmental factors of materials of EV batteries in an energy system model?
- Design a methodology to represent social and environmental factors as well as supply side constraints of materials in energy system models (ESMs).
- Improve the spatial and temporal representation of future (2030, 2050) transport demand in the highRES model.
- Collaborate and exchange with other Nordic modelling teams and researchers to refine the methodology for the two previous points above.

The work presented by UiO in this report, including methodologies and results, is a part of ongoing research and will be subject to future work and publications.

1.4. WP4 Team

DEA

The Danish Energy Agency (the DEA) is a government agency operating under the Ministry of Climate, Energy and Utilities in Denmark. Its primary responsibility revolves around formulating and implementing policies, strategies, and initiatives related to energy and climate matters, with its work spanning a wide spectrum of activities such as energy planning, regulation, research, and international collaboration. The DEA's research team in WP4 consists of members from the Centre for Systems Analysis.

IVL

IVL Swedish Environmental Research Institute is an independent, non-profit research organisation owned by a foundation established by the Swedish government and industry. The institute comprises Sweden's largest groups of environmental experts and employs around 400 people, making IVL a leading institute for applied environmental research and consultancy services. IVL undertakes research projects and contract assignments in the areas of natural resources, climate and environment, resource-efficient recycling and consumption, sustainable production and environmental technology, sustainable urban development, and transport. The unit of Sustainable Cities and Society has participated in WP4, with a team that includes expertise in modelling the energy system, the transport sector, and emissions to air and abatement costs as well as environmental and health impact of the emissions (e.g., using the ON-TIMES Model and the GAINS model). The ON-TIMES (Open Nordic Times) model has been jointly developed by several Nordic modelling teams, with IVL being one of the leaders of the work. The GAINS model is developed by IIASA and IVL has jointly with IIASA developed a Nordic version of the model.

IFE

The Institute for Energy Technology (IFE) is an independent, non-profit, private research organisation and is a key Norwegian actor specializing in energy issues. IFE conducts research at both national and international levels and is involved in more than 300 international projects in the fields of: energy system analysis, renewable energy, geothermal energy, bioeconomy, environmental technology nuclear technology, reliability, digitalization, and man-machine systems. IFE's research team in WP4 consists of members from the Energy System Analysis department.

UiO

The energy systems modelling group is part of the department of technology systems at the University of Oslo. It has as primary research focus to support the transition to sustainable future energy systems that meet the Paris Agreement Goal. The group develops and use energy system models with a focus on systems with high shares of variable renewable energy sources (i.e. wind and solar energy) such as the highRES model. Among other things, we are currently exploring the inter-annual variability of weather, designing systems that are weather and climate resilient, the role of seasonal storage using hydrogen and hydropower as well as social acceptance and socially just energy systems.

SINTEF

SINTEF is a multidisciplinary, independent research organisation located in Norway. SINTEF is a broad, multidisciplinary research organisation with international top-level expertise in the fields of technology, the natural sciences, medicine and the social sciences. The research team in WP4 consists of members from SINTEF Community and SINTEF Energy covering areas of expertise in sustainably mobility, transport demand modelling and energy system modelling.

2. Representation of transport in applied models

2.1. Tabular overview

The main properties of the models used in WP4, focusing on the transport sector, are described in Table 2-1.

Table 2-1: Model properties

	Transport modes covered	Temporal resolution	Input data	Data sources
IFE-TIMES-Norway	Air, sea, rail and road	Annually, Time-slices for EV charging profiles	• Demand projections for transport services and energy demands • Costs of technologies • Technical efficiencies and potentials • Fossil fuel prices	Diverse sources [17], [18],(transport models, national statistics and plans)
highRES	Road transport	Hourly	• Costs of technologies • Land availability for renewables • Weather data (renewable capacity factors) • Electricity demand (including electric transport)	Diverse sources: The Energy Map [19] for spatial distribution , future demand scenarios [20], EV load curves [21]
Energy Map	Air, sea, rail and road	Daily	• Traffic flow • Vehicle, aircraft, and vessel specifications • Transport network	Transport models, NVDB
GENeSYS-MOD	Air, sea, rail and road [22]	Annually; within-year time slices	• Energy system cost parameters • Exogenous energy demand • Fossil Fuel Availability and Prices • Renewable Technologies and Potentials	Assumptions from World Energy Outlook and previous research [22]
ON-TIMES Model	Air, sea, rail and road	One to five years, with yearly time resolution of 32 time slices	• Demand projections for mobility and energy demand • Cost and performance of energy conversion technologies for the transport as well as other energy sectors • Cost and potential for energy sources • Emission factors and CO_2 emissions cap/targets	Diverse sources including e.g. Nordic Energy Technology Perspectives (NETP) 2016, national and EU statistics, technology assessments etc. [7]
GAINS Model	Air, sea, rail and road, mobile machinery	Five-year intervals until 2050	• Combinations of fuel use and fuel technologies	Diverse sources; country specific inventories and estimates, European scale models

2.2. IFE-TIMES-Norway

Overview

IFE-TIMES-Norway is a cost optimisation model of the Norwegian energy system [17], based on the TIMES (The Integrated MARKAL-EFOM System) modelling framework [23]. The model provides a detailed bottom-up representation of the system including resources, energy carriers, conversion technologies, and demands aggregated into five regions corresponding to the electricity market's spot price areas in Norway.

Moreover, the model can provide long-term investments and operational decisions in both supply and demand technologies to meet future energy demands towards 2050, with model periods for every fifth year from 2020 to 2050. To capture operational variations in power generation and energy demands, each model period is split into 96 sub-annual time slices, corresponding to 24 hours for each of the four seasons of the year. The mathematical formulation of the model aims to minimise the total discounted cost of the energy system including investment costs in supply and demand technologies, operation and maintenance costs, and income from electricity export to and costs of electricity import from countries outside the model, while meeting the demands for energy services in each of the modelled years.

Representation of transport demands in IFE-TIMES-Norway

The representation of the transport sector in IFE-TIMES-Norway captures different road and non-road transport demands and vehicle segments. In the model, road transport demands are divided into six different types consisting of demands from cars, vans, buses, and 3 different heavy-duty truck segments [17], [18]. The demands for these different road transport segments are expressed as demands for transport services.

In addition to these, railway transport demands from trains are also considered for inland transportation. The model also captures non-road transport demands from the maritime and aviation sectors. In the case of maritime demands, these are further subdivided for passenger and fishing, as aggregated vessel segments. Moreover, freight vessels are also included and are further disaggregated to include the transport energy demands of 5 different freight segments based on the data inputs from the Energy Map [24]. An overview of the different transport demands considered in the model is presented in Table 2-2.

In the IFE-TIMES-Norway model, different combinations of propulsion technologies and commodities can be used to meet the transport demands mentioned above. For example, the model includes internal combustion engines (ICE) as a potential technology investment with the option to use fossil fuels (petrol, diesel, natural gas, MGO, or jet fuel – depending on the transport type), or the analogous fuel replacements with liquid biofuel or biogas. The option of ammonia-powered ICEs is also implemented in the model for the maritime vessels. In addition to these, plug-in hybrid with ICE, battery electric vehicles, and hydrogen fuel cells are also implemented in the model as potential technologies options.

Improved transport sector representation in IFE-TIMES-Norway

As part of the work conducted in WP4, the representation of the transport sector in the IFE-TIMES-Norway model has been improved by including alternative technologies to further explore the emerging options for decarbonising hard-to-abate segments within transport, focusing on aviation. Namely, these include the production of synthetic fuel pathways for the production of jet fuel to cover fuel demands in the aviation sector, as well as carbon capture and utilisation options within this sector like the use of direct air capture to provide the CO_2 feedstock for synthetic fuel production [25].

Table 2-2: Overview of the transport demand types and segments in IFE-TIMES-Norway [17].

Transport demand	Type	Segment
Road Transport	Cars	
	Vans	
	Buses	
	Trucks	Small Trucks
		Short haul trucks
		Long-haul trucks
Railway transport	Trains	
Non-road transport		
Aviation	Domestic flights	
Maritime	Passengers	
	Fishing	
	Freight	Container
		Bulk
		Cargo
		Tankers
		Other

2.3. Open Nordic TIMES Model (ON-TIMES)

Overview

The ON-TIMES (Open Nordic TIMES) model is based on the TIMES modelling framework and is open access. The model builds on the TIMES-Nordic model developed in the NER funded project Shift (https://shift.tokni.com/) and further developed in the Nordic Clean Energy Scenarios 2020 project (https://www.nordicenergy.org/project/nordic-clean-energy-scenarios-solutions-for-carbon-neutrality/). The model is a bottom-up, optimisation (cost minimisation) energy system model with comprehensive coverage of the national energy system including besides the transport sector also power and heat, industry, service sector, and residential sector. The model covers Sweden, Norway, Denmark, Finland, and Iceland. Each country is modelled individually and is geographically aggregated into different regions that are interconnected through the representation of transmission lines, allowing e.g., electricity trade. The model has a yearly time resolution of 32 consequential time slices representing seasonal (four seasons), weekly (working/non-working days) and daily variations.

The ON-TIMES model is used for producing scenarios showing pathways to Nordic carbon neutrality. It is suitable for this project as it covers the entire energy system but also includes a detailed representation of the transport sector in the Nordic countries. The development in other sectors influences the development in the transport sector and the emissions of air pollution. The ON-TIMES model covers the five Nordic countries (Denmark by two regions, Sweden by four regions, Norway by two regions, Finland by two regions, Iceland by one region) in detail, whereas the surrounding countries are represented by trade-links and price profiles for traded commodities. Sectors represented in the model are upstream/ fuel production, power and heat, heavy industry, residential, transport and other (i.e., manufacturing industries, services, and agriculture). The model has a time horizon between 2015 -2050, in 5-year time steps. Each model year is divided into 32-time slices. ON-TIMES can be soft-linked to the BALMOREL model, which analyses dispatch and operation focusing on the electricity system [26]. The main model inputs to ON-TIMES are techno-economic data of existing energy conversion technologies; current and future resource potential; fuels prices and (if relevant) the associated CO_2 emissions; demands projections for different energy services; techno-economic data of new conversion technologies which are used as investment options; and model constraints, e.g., CO_2 emissions cap. The entire ON-TIMES energy system model is available on GitHub – Nordic Energy Research NCES [7]. It contains all sector-level technology data and all demand projections with the associated references.

For each scenario and model year, the primary model outputs are installed capacities of energy conversion technologies, fuel use, production per conversion technologies and marginal energy and CO_2 prices. The model also generates results for primary energy supply by energy source, CO_2 emissions, investment capacities, carbon capture level, final energy consumption by energy source, and final energy consumption by sector. The representation of the transportation sector is presented in Table 2-3.

Table 2-3: Representation of the transportation sector in the ON-TIMES model

Transport demand	Type
Passenger transport	Car
	Bus
	Train
	Biking
	Walking
	Ferry
	Aviation
Freight demand	Van
	Truck
	Train
	Ship
	Aviation
International transport	Modelled separate from national transport

Each national transport sector comprises all passenger and freight transportation, both characterised in terms of mobility demands and end-use transport technologies. Fuels can either be traded in the international market or produced by Nordic refineries, bio-refineries, or other production technologies (such as electrolysers and electrofuel facilities).

Representation of transport demands in the ON-TIMES Model

Passenger and freight air and marine transport is described by a selection of fuel and vehicle technology options, including conventional jetfuels and marine fuels, biomass based jetfuels and marine biofuels, hydrogen and electrofuels. Fuel options for road transport include conventional fossil fuels, biofuels (liquid and gaseous), electricity, hydrogen, electrofuels and for the case of heavy road transport also electric roads. Rail (metro, train, light rail) and non-motorised modes such as biking and walking are also included.

Each transport sector in the ON-TIMES Model is divided into inland, aviation and navigation. Inland passenger transportation comprises ten modes: car, bus, coach, rail (metro, train, light rail), twowheelers (motorcycle and moped) and non-motorised modes (biking and walking), while the inland freight sector comprises three modes: van, truck, and rail. Aviation and navigation comprise one mode each, namely aircraft and ship. Both domestic and international aviation and shipping as well as domestic road transport is included.

The mobility service demands are defined exogenously for each mode for the entire time horizon in the form of passenger-kilometres (pkm) and tonne-kilometres (tkm). The mobility demands are mainly based on the national transport statistics that are projected up to 2050.

Modal demands are split further into distance range classes. For the inland passenger, these are extra short (<5 km), short (5–25 km), medium (25–50 km) and long (>50 km). For passenger navigation and aviation modal demands are split into National and International. Freight modal demand are split into national short (<50 km), national long (>50 km) and international except for rail and ship where national demand segments are not split and freight aviation that only comprises the international demand. Each transport mode is characterised by a defined travel pattern, representing the percentages travelled in the different distance classes. In the case of passenger transport, travel patterns reflect population travel habits, while for freight they represent typical modal adoption with respect to distance. Travel patterns are country-specific quantities, which can also vary across regions. Moreover, an elasticity of substitution is defined for each distance category, allowing the model to adjust the modal demands defined in each category based on changes in their shadow price stimulated by the CO_2 target under study.

Assessing the environmental effects of Nordic transport transition pathways towards climate neutrality

In this assessment the results in terms of use of various fuels and transport technologies from scenarios for different decarbonisation pathways for the Nordic transport sector using the ON-TIMES model will be used as basis for assessing the potential impact on the most common emissions of air pollution including NOx and particulate matter. As other emissions than GHG is not included in the ON-TIMES model the GAINS model (see next section) will also be used for this assessment. To represent clearly distinct levels of various options (such as electrification) additional scenarios are developed in the ON-TIMES model.

2.4. Gains Model

Overview

The GAINS model developed by IIASA [27] estimates emissions to air and abatement costs as well as environmental and health impact of the emissions. The model explores cost-effective emission to air control strategies that simultaneously tackle local air quality and climate gases to maximise economic and environmental benefits. The model covers emissions of ten air pollutants and six climate gases. Emission projections are being specified in five-year intervals until 2050. IVL has jointly with IIASA developed a Nordic version [28].

Representation of transport sector in the GAINS Model

In the GAINS model, the transport sector has the same structure as the rest of the model. The categories are combinations of the two main components in the structure: the Activity and the Technology. The activity in GAINS is basically expressed as fuel use, which cause one or several processes that in turn cause emissions to air. These processes can roughly be divided into three types:

combustion of fuels, mechanical processes, and electricity use. Combustion of fuels causes emissions of climate gases and air pollutions, mechanical processes cause emissions of air pollutions (mainly particles), and electricity use in GAINS does not cause any emissions to air when it is used.

The technologies in the transport sector are all mobile, and therefore measured in number of units of different vehicles, vessels, and crafts, in different sizes. The size of the unit is aimed to describe the emission patterns, and may be expresses as vehicle type, engine effect, gross tonnage or in other units depending on the vehicle type and the transport subsector.

The sector is overall divided into transportation by road, other non-road mobile sources, and sources from the so-called national sea traffic. The latter includes seagoing ships and fishing boats operating between the ports in the same country. Each of the major sectors is additionally divided into more detailed vehicle categories. The most important sector, the road transport, are divided into the following vehicle categories:

- Motorcycles, mopeds, and cars with two-stroke engines
- Motorcycles and mopeds with four-stroke engines
- Cars and small buses with four-stroke engines
- Light commercial trucks with four-stroke engines
- Heavy duty buses
- Heavy duty trucks

For each vehicle type GAINS needs information on total annual fuel consumption by fuel type (in energy units), total annual vehicle-kilometres driven, and vehicle numbers. Fuel consumption, kilometres driven, and vehicle numbers are closely related. Other transport non-road sources are divided into the following categories:

- Mobile machines in construction and industry. If this consumption is not known from national statistics, GAINS assumes default shares for different fuel used and share used in mobile sources, within the construction and industrial sectors, as well as other manufacturing industry.
- Tractors and mobile machines in agriculture and forestry. If there is no country specific information about fuel consumption, GAINS assumes a default share of agricultural gasoil consumption that is used by mobile sources.
- Inland waterways
- Railways
- Civil aviation. Following methodology used by IEA.
- National maritime shipping, which means movement of ships between ports in the same country and fishing vessels. The vessels are subdivided into large (>1000 gross tonnage) and medium (<1000 gross tonnage). International marine bunkering is not included, neither emission from international sea traffic.
- Vehicles and small machines with two-stroke engines: loan movers, garden tools, handheld saws, privately used motorboats and snowmobiles.
- Other non-road sources with four-stroke engines: small household and forestry machines, military vehicles and motorboats. Use of gas by pipeline compressors are also included.

For each vehicle type, GAINS needs information on total annual fuel consumption by fuel type (in energy amount), and number of vehicles. For transports activities that implies mechanical processes like wearing between wheels and the road surface in road traffic, vehicle-kilometres are also needed. As fuel consumption and vehicle numbers are closely related, consistency of these two data sets needs to be carefully checked so that for each vehicle category, average fuel consumption is within realistic range and corresponds to policies in each scenario.

Assessing the environmental effects of Nordic transport transition pathways towards climate neutrality

In this assessment a modelling tool for linking and transferring data between the ON-TIMES model and the GAINS model is developed. By using this tool an initial assessment of the potential impact on air pollution of selected pathways for decarbonising the transport sector in selected Nordic countries can be performed.

2.5. The Energy Map

Overview

The Energy map is a model developed at SINTEF that calculates the energy demand from the transport sector in Norway [24]. It is based on road network data from NVDB (National Roads Database) and traffic data from Norwegian transport models. Given sufficient input data, it can be used to estimate the energy demand for past years, the current year, or projections for the future. The Energy Map model was further developed in the FuChar project to convert the energy demand to a charging demand from vehicles by refining the temporal resolution and properties of the estimated trips. FuChar is a knowledge-building project financed by The Research Council of Norway and aims to minimise investment and operating costs related to the grid integration of electric transport. This includes analyses of transport patterns, user behaviour and charging profiles from electric vehicles and vessels.

The vehicle fleet (the distribution of various vehicle types) used in the Energy Map is based on country-wide vehicle statistics with an extrapolation based on both current developments and government policies to get predictions for future fleet distributions. The energy demand from the various vehicles in the Energy Map is calculated using physics-based vehicle models, which simulates driving the vehicles and vessels through a highly detailed description of the network geometry along a given route. The traffic data from the transport models is used to run the calculations on all roads in the Norwegian transport network. Traffic volumes and vehicle type distributions are used to aggregate the single vehicle energy demand on single routes into the full vehicle fleet energy demand for the entire network.

The Energy Map tool is constructed with a high level of detail, allowing users for instance to investigate energy demand on small sections of individual road links, or aggregate the demand up to municipalities or counties, or to substations and transformers. The resolution of the calculations is detailed in spatial and temporal dimensions, which calls for a similarly detailed set of inputs regarding transport network and vehicle characteristics.

Representation of transport demands in the Energy map

The main input to the Energy map is from an array of transport models developed to represent the Norwegian transport sector. These models are used to estimate the amount of transport and how this change given specific scenarios. There are three types of transport models used in Norway for estimating the impacts of the National transport plan. The first type is passenger transport models, which are further divided into regional and national models. While the national model cover travels over 70 km, the rest is covered by 5 regional models (North, South, West, East and Middle Norway).

The geographical extent of the regions is similar to, but not exactly overlapping with, the power-price regions in Norway. The second type is for freight transport, which consist of one national freight transport model.

The interaction between specific transport models is handled by establishing fixed outputs for other models. For example, the regional transport models include a fixed representation of freight transport and long-distance transport with origins or destinations outside of the region. In the Energy map, all these models are integrated into one complete representation of the Norwegian transport sector. This is done by removing static transport representation and any other overlapping input across models.

The input for the passenger transport models is a set of properties describing the main factors affecting travel demand and travel behaviour. First, a demographic description is required in the form of data on residential population, workplaces, and socioeconomic characteristics of the population. For each geographical zone in the model, the number of people is given based on available statistics and official prognoses for future population changes. Recently, a tool is developed to consider house and workplace construction plans of municipalities. Second, the travel demand and travel behaviour are estimated based on empirical data collected through national household travel survey and information about car ownership. Transport supply description for passenger transport is provided into the model in the form of road networks and public transport service. Road network details are taken from National Road Database (NVDB) [29] and public transport services are mainly imported from Entur, which is a Norwegian Database for public transport services [30].

The passenger transport model follows a traditional four-step modelling [31], where the first step assigns a number of trips to and from each area based on the aforementioned factors including residential population, workplaces, type of the workplace, etc. In the following steps, the model assigns the generated trips to origin-destination pairs, specific modes, and specific routes. The assignment processes are based on random utility theory, where the traveller compares different alternatives and their associated costs in each step and chooses an alternative that maximises their utility [31]. The generalised cost for each alternative, which is an important factor in the choice model, consists of all costs related to the trip, such as travel time, energy price, ticket cost, toll fare, parking fees etc. The output of the passenger models, both national transport model and regional transport models, is the number of trips with each mode between zones and the route they will choose.

For freight transport, data about the terminals, type of the commodity, and goods flow is exogenously provided to the model with the projections for future years. The model estimates the origin destinations freight flows optimising mode of transport, size, and frequency of the freight which consequently affects the required number and type of the vehicles [32]. Route choice for land freight transport is modelled in combination with passenger transport.

The Energy map uses input from transport models to estimate and visualise a detailed energy demand from the transport sector. By considering vehicle specific power, the model estimates the speed and power profiles for all vehicles, vessels, aircrafts, and trains along routes [24]. Predicted energy carrier shares are used to estimate future energy use in prognosis years. Methodology for allocating energy use to charging and refuelling locations is developed in the FuChar project, based primarily on estimated tolerances for range and other preferences.

2.6. GENeSYS-MOD

Overview

Global Energy System Model (GENeSYS-MOD) is an open-source linear program aiming to find the cost-efficient way to satisfy the provided energy demand over the years, respecting a set of exogenous constraints, mainly related to CO_2 emissions [22]. It is based on open-source energy modelling system (OSeMOSYS) framework; however, it enhances the framework by including a modal split for transport, an improved trading system, and changes to storages. Exogenously defined energy demands are classified into three main categories: electricity, heating, and transportation. The details of the current energy system (2018) provide the starting point to the model, together with resource potentials, emission intensities and costs associated with the different fuels and technologies.

The current version of the openly available European dataset is developed within the openENTRANCE project and contains 4 different scenarios through which Europe can reach a decarbonised energy system in 2050, see [33] for details. Results from the model for four different European decarbonisation scenarios are openly available through the open Platform of openENTRANCE [34]. The analysis of Norway has been conducted both for Norway at a country level (one node) and on a more detailed subnational, power-price region level (5 nodes).

In Norway, Hydropower is the main source of power generation in decarbonised energy system in all 4 scenarios generated in openENTRANCE project[34]. Initiated with non-Nordic focus, however, GENeSYS-MOD has significant simplifying assumptions on modelling hydropower from reservoirs, not accounting for the inflows, restrictions on water levels or reservoir size, cascaded systems etc. Still, power trade and power infrastructure are included in the model and investment in infrastructure will be adapted to the high degree of electrification that is predicted. In GENeSYS-MOD, the demand for heating and transport can be covered by different energy sources, and the model will calculate the optimal combination of sources and infrastructures.

Adaptation of methods for iterative modelling of transport and energy systems

There are several parameters which are handled in both GENeSYS-MOD and the Energy map and transport models, although they are differently handled in the two sets of models. Example of these parameters include mobility demand, modal split, CO_2 prices, and power prices. In the following, these parameters are briefly discussed aiming to identify the potential to use them as linking points between the models. Linking the two models can improve potentials of the models for analysing the effects of electrification of transport in the two models by taking more relevant factors into the consideration.

Mobility demand and the modal split are the main result of the transport models and are endogenously estimated to a large extent especially in the passenger transport models. The demand is dependent on the demographics and mobility needs of each socio-demographic group in the population. It is worth mentioning that since the models are calibrated for the current situation, the demand elasticity to price and other determinant factors might not be properly reflected if the scenario significantly deviates from the current situation. In the freight transport model, however, the demand is basically exogenously estimated on zone-pair level, while the modal split and vehicle requirements are estimated endogenously in the model considering cost of transporting commodities with each mode, although not differentiating vehicles by type of fuel. On the other hand, the demand for mobility in GENeSYS-MOD is exogenously and separately defined for passenger and freight transport.

Based on a system-optimal perspective, GENeSYS-MOD gives a modal split for both passenger and freight transport. For freight transport, the model can cost-effectively assign the demand to road, rail, and ship, while the passengers can be transported by road, rail, and air. For each mode, there exist lower bounds as constraints which control that the model result proposes a minimum usage of the specified mode. The optimal combination of modes is endogenously set by the model based on energy consumption rates for each mode, aiming to minimise costs/consumption rate. On the other hand, the modal split in the passenger transport and freight transport models are based on user-optimal perspective. Each mode is associated with a generalised cost, which includes time, distance, and direct cost of mobility. A mode which has the lowest generalised cost in relation to the other modes is more probable to be chosen by the user. The preferences of the users might differ based om they socio-demographic groups in the passenger transport model.

The results from GENeSYS-MOD can be used to derive CO_2 price and power price as they are shadow prices associated with emission constraint and power constraint. Both the CO_2 price and power price significantly affects the cost of transport, although it might affect different mode to a different extent.

GENeSYS-MOD produce results for each year, and for specified within-year time-slices. For instance, a year can be divided into seasons, day types (e.g., weekday/weekend) and daily time brackets (e.g., day/night), all defined as fractions of a year. In the Energy map and the associated transport models, the results are mainly produced and presented daily, with the focus on weekday and not accounting for seasonality in mobility demand. The results are aggregated to a full year for reporting purposes for the Energy map by applying established factors for the relation between a working day and a year. Any introduction of seasonal variations would require a substantial development of the transport demand prediction models.

The regional resolution of the models differs considerably. The regional passenger transport model is a network-based model which uses the basic statistical unit (Grunnkrets) as the geographical unit. Basic statistical unit is a type of statistical unit used by Statistics Norway to provide homogenous geographical units for regional statistics in Norway. While the national passenger model and freight model use a more aggregate network for modelling transport, GENeSYS-MOD has a very aggregate approach for regional modelling as it uses 5 different power-price regions.

Representation of transport demands in GENeSYS-MOD

Passenger and freight transport demands are exogenously defined in GENeSYS-MOD for every region and each year. Compared to the initial OSeMOSYS version, GENeSYS-MOD includes more options in the transportation sector, as it is extended to include a modal split for transport for the distribution of passenger or freight kilometres of a particular type of transportation.

The modal split for the transportation sector is exogenously given, and based on data from 2015-scenario from the World Energy Outlook [35], using a regional differentiation. In contrast to strictly defined modal split in 2015-scenario, these constraints are loosened in GENeSYS-MOD to a lower-bound to let the model find the optimal solution.

The output of the model for the transport sector is the most cost-effective combination of mode, technology, and fuel, considering the exogenously defined emission constraints.

2.7. highRES

Overview

The high spatial and temporal Resolution Electricity System model for Europe (highRES-Europe) is a power system model specifically developed for analysing electricity systems with a large amount of variable renewable energy technologies (VREs) such as wind and solar. The model is a linear optimisation model, with the objective to minimise the total system costs, which includes both operation and annualised investment costs. highRES-Europe is a snapshot model at an hourly resolution (8760 time slices) with 31 zones represented (EU27 + Iceland, Norway, Switzerland and United Kingdom). The current version of highRES-Europe therefore represents countries at a national level but can be disaggregated (as is done in highRES-Norway) or aggregated depending on the spatial scope of the analysis and availability of data. The model represents the transmission network through a linear transhipment formulation and includes a hybrid greenfield approach where neither existing transmission nor generation infrastructure is predetermined, except for installed hydropower capacities (storage and generation). The demand-supply balancing equation ensures that the electricity supply in each of the zones, through local electricity generation, storage or import, is greater than the demand in every hour. Power plant operations are subject to technical constraints, such as ramping restrictions, minimum stable generation and start-up costs for thermal power plants. The annual electricity demand and carbon budget can be sourced from the output of long-time whole energy system models.

HighRES-Europe uses historical meteorological data from climate reanalysis (e.g. ERA-5 reanalysis produced by ECMWF and processed by Atlite [36] in physical power generation models to model capacity factors for wind, solar and hydropower. The variable and spatially unrestricted renewable energy technologies (i.e. wind and solar) can be modelled either at a grid-cell resolution of 30x30km, or aggregated on the applied zonal level of the model. The highRES modelling framework is illustrated in Figure 2-1 below. A more detailed description is provided in Price and Zeyringer [37] and the model structure is openly available on GitHub [38].

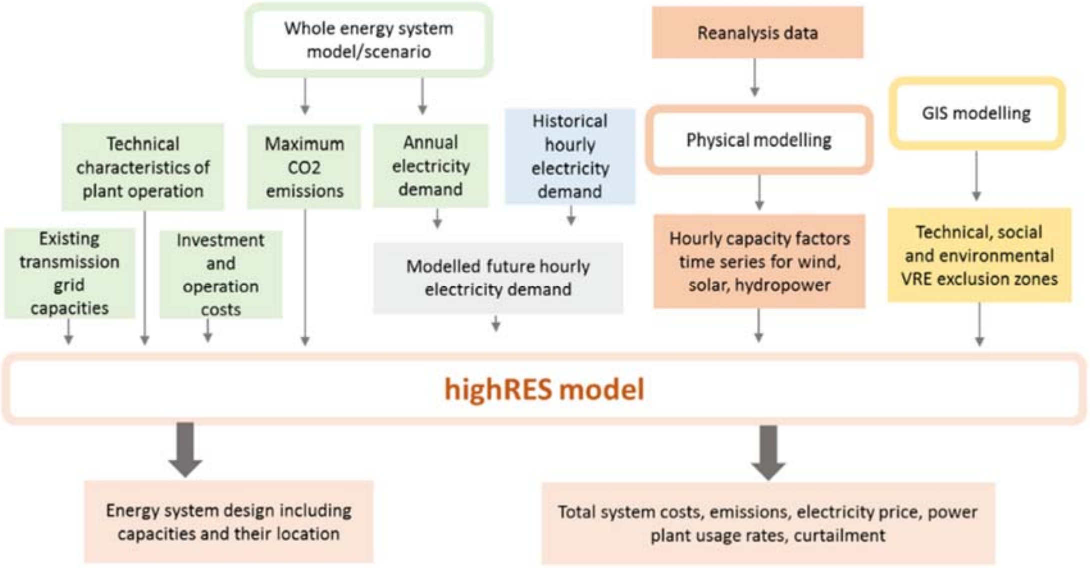

Figure 2-1: The highRES modelling framework. Figure from [37]

Improving the spatial and temporal resolution of electric transport demand in highRES-Norway

In highRES, transport demand is modelled as an electricity demand, meaning that only electrified transport is covered by the model. For this work we are only considering electrified transportation in Norway. A version of highRES only modelling Norway is used (highRES-Norway), where each county is considered as a zone in the model. To model the future electricity system, demand scenarios for the future are needed. For this work, demand scenarios from Statnett [20] are used for the electricity demand in Norway for 2030 and 2050. Statnett developed three scenarios for each year: low, high and extra high. Here we employ the high demand scenarios. These scenarios show an increase in electricity demand from 140 TWh in 2022 to 178 TWh and 260 TWh in 2030 and 2050 respectively. For electric transport, the demand increases from 3 TWh in 2022 to 13 TWh in 2030 and doubles to 26 TWh in 2050.

The 2022 electricity consumption is used as a baseline for future demand, on which the reported changes in demand are added. The model is run with historical weather data, so the corresponding historical consumption data should be used as a baseline. To solve this, the historical consumption is scaled so that the average over all years equals the 2022 consumption level (ensuring that the yearly variation is kept). The aim is to implement the demand from electric transport on an hourly temporal scale and a spatial scale corresponding to the counties of Norway. The starting point is the 10 TWh increase from 2022 to 2030 and 23 TWh increase from 2022 to 2050 for electric transport.

To aggregate the electricity demand from transport to county level we use results from the Energy Map [19] (cf. Section 2.5). The main challenge is that the results from the Energy Map and Statnett's scenarios does not correspond (this could be due to many reasons, for instance different assumptions around the future development of the demand). The approach is to use the spatial distribution of demand from the Energy Map to spatially distribute the 10 TWh and 23 TWh increase in electric transport demand for 2030 and 2050 respectively. From the electric transport demand in the Energy Map, the share of total demand for each region is calculated. This share is used to distribute the demand from Statnett's scenarios.

Once the spatial resolution is resolved as described above, we move on to the temporal resolution. Two cases with different assumptions and their effect on the energy system is investigated. The first assumption is that the electric transport demand is uniformly distributed throughout every day of the year. The next assumption is that the same daily load curve applies to every day of the year. These assumptions are not accurate and will be the subject of further work on the topic. The load curve is then finally used to distribute the daily demand to an hourly resolution.

Figure 2-2 below shows how the daily demand curve changes (the figure shows the base, 2030 and 2050 demand curve for one zone, NO03 Oslo, and one day, 15.06.2021) when implementing the temporal distribution of the electric transport (the 2030 and 2050 curves also include the increased demand from other sectors). The effect of the temporal distribution of the electricity demand from transport is apparent in the figure. Comparing the base electricity demand (the blue line in the figure) to the electricity demand for 2030 and 2050 (orange and green lines respectively) with the disaggregated electricity demand from transport there are differences in the hourly demand curve. The main difference is in the afternoon, especially between 14:00 and 18:00, where a peak appears for 2030 and 2050 which is not present in the base case.

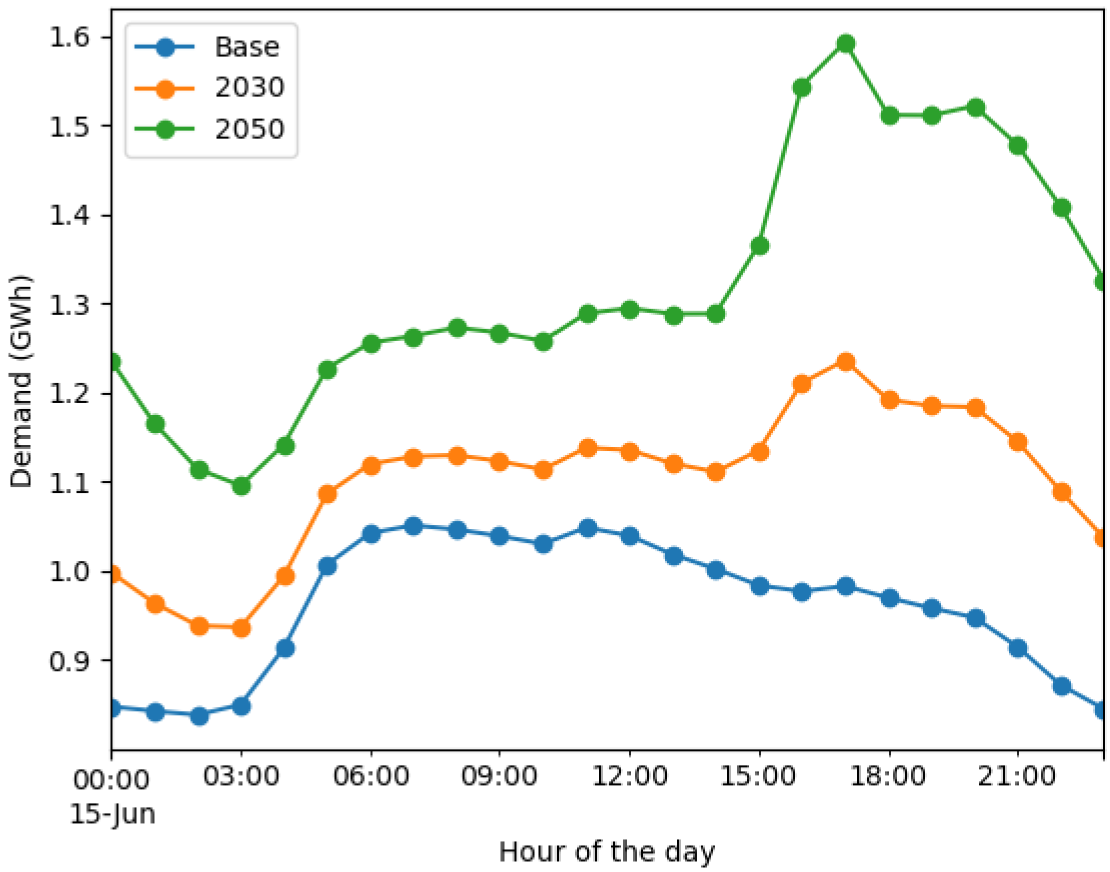

Figure 2-2: Demand curve for Oslo on 15.06.2021 for the base case (historic weather data) and with the 2030 and 2050 additional demand added.

3. Results

3.1. Overview

This chapter describes the results from the work in WP4. There are different types of results. A set of numerical energy system models (ON-TIMES, GAINS, IFE-TIMES-NORWAY, highRES, GENeSYS-Mod) and their data been improved, applied to analyse transport-related research questions, linked together, and new scenarios have been developed. In addition, we describe qualitative research performed and a workshop series that has been carried out to discuss important topics for the work.

For some of the quantitative models (i.e., the ON-TIMES/GAINS model and the IFE-TIMES-Norway model) assumptions were set to represent a common narrative.

3.2. Environmental effects of Nordic transport transition pathways towards climate neutrality

The assessment of environmental effects of Nordic transport transition pathways towards climate neutrality includes four tasks that are described in short below. Analyses are carried out by use of ON-TIMES, and in combination with the GAINS model for some tasks.

Scenarios for decarbonising the Nordic transport sector

Work was based on policy instruments and ambitions aimed for achieving a low-carbon transport sector by 2050 in the Nordic countries and the Nordic Clean Energy Scenarios 2020 and Shift projects. Five scenarios were developed for decarbonising the Nordic transport sector and achieving climate neutrality. The scenarios represent different assumptions related to the introduction of certain type of key measures and options including e.g., scenarios having varying levels of electrification, biofuels for transport, hydrogen, electrofuels, modal shift and transport demand. Scenario assumptions and insights was shared with the other partners in the project via a workshop and bilateral meetings.

The first scenario, **CNN**, is based on the Carbon Neutral Nordic (CNN) scenario used in the Nordic Clean Energy Scenario 2020 project. The CNN scenario represents a scenario that seeks the least-cost pathway for meeting the Nordic carbon neutrality target considering current national plans, strategies, and targets.

The second scenario tested, **CNN+bio restriction (in short CNN BIO)**, represents the CNN scenario but with the biofuel constraint representing the limited global bioenergy potential also developed in the Nordic Clean Energy Scenario 2020 project as a sensitivity assessment, added. In terms of fuel use and shift and impact on the assessed emissions in the transport sector in Sweden, Norway, and Denmark there is only a minor impact in this scenario compared to the CNN. Thus, this scenario is not discussed further because the results are similar to the CNN case.

The third scenario, **CNN+less electrification (in short CNN ELC)**, is based on the CNN scenario but with restrictions on the electrification of transport (to illustrate the impact of a lower electrification rate for the transport sector that in the CNN case as this rate is relatively high in all the assessed Nordic countries in the CNN scenario).

The fourth scenario, **CNN HOPE**, is based on the CNN scenario but in this case most of the shipping related data in the ON-TIMES model has been updated using the assumptions made in the Hydrogen fuel cells solutions in Nordic shipping (HOPE) project resulting in a higher level of hydrogen and methanol in the Nordic shipping sector. The updating of data include the demand for shipping and the performance for marine fuels, propulsion and vessels that has been updated in terms of investment cost, operation and maintenance cost, tons per vessel and utilisation factor (maximal km/year/vessel) (see [39]).

The fifth scenario, **NPH**, represents the Nordic Powerhouse scenario in the Nordic Clean Energy Scenario 2020 project where the Nordics provide more clean electricity, clean fuels, and carbon storage for the European transition towards lower GHG emissions.

The total fuel use in the transport sector in the CNN scenario in the Nordic region (represented by Denmark, Norway, and Sweden) is presented in Figure 3-1. The national transport fuel use in the included scenarios for Sweden, Norway, and Denmark, respectively, is illustrated in Figure 3-2, Figure 3-3 and Figure 3-4. CNN is characterised by strong electrification in the road transport sector. There is also an increase in synthetic natural gas (representing methane based on hydrogen or bioenergy, sometimes combined with carbon capture and storage) and introduction of biomass-based kerosene for the aviation sector. The fuel choices in the CNN+bio restriction scenario resemble the CNN scenario and are almost identical for 2030 and 2040 for all the included Nordic countries. There is somewhat less electrification for road transport in the CNN+less electrification (CNN ELC) scenario than the CNN scenario. Which transport fuels increase to compensate for the lower electrification varies somewhat between the countries and include biodiesel (all countries), biomass-based kerosene (Denmark and Sweden) natural gas (Denmark and Norway), synthetic natural gas (Denmark and Norway), hydrogen (Denmark and Norway), and ethanol (Sweden). The NPH scenario does not differ that much from the CNN scenario but contains a slightly lower use of electricity (but higher than in the CNN+ less electrification scenario). Across all scenarios analysed, kerosene (fossil based) is gradually being phased out after the year 2030, with biokerosene emerging as an alternative solution for all countries considered. Meanwhile, natural gas is being reduced incrementally following 2030 and is being swapped for synthetic natural gas. Aside from electrification measures, these trends around the substitution of kerosene and natural gas by more sustainable alternatives hold across the studied period.

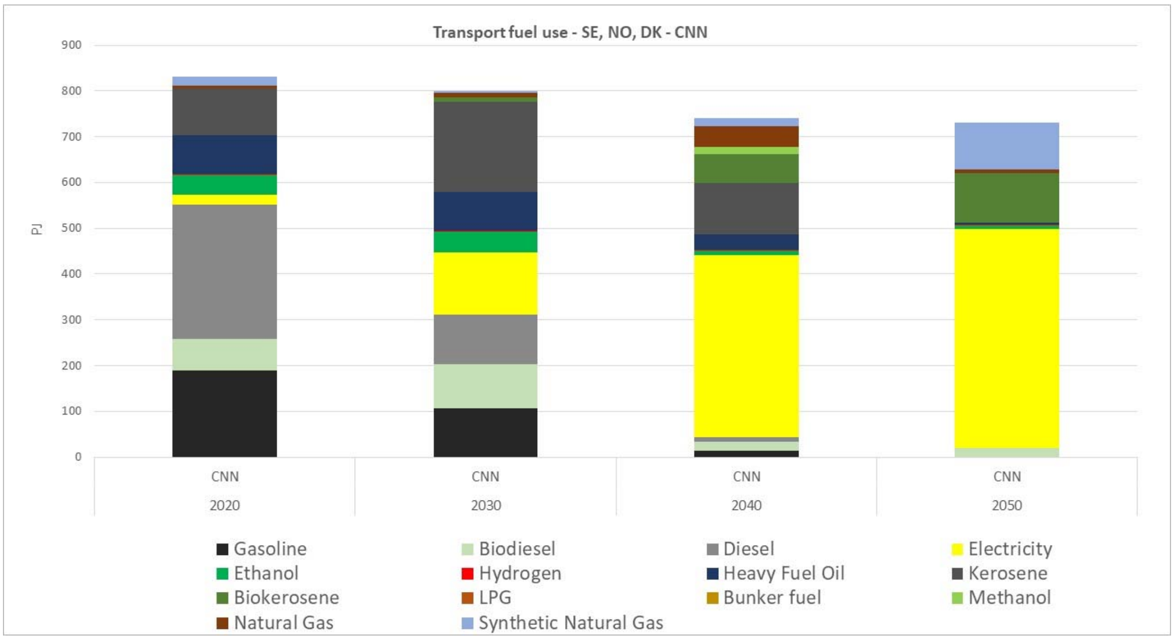

Figure 3-1: Cost-effective fuel choices in the total Nordic transport sector (represented by Denmark, Norway, and Sweden) in the CNN scenario using the ON-TIMES model. For scenario description see the text. Synthetic natural gas (methane) is based on hydrogen or bioenergy, sometimes combined with carbon capture and storage, CCS. LPG represent Liquefied petroleum gas.

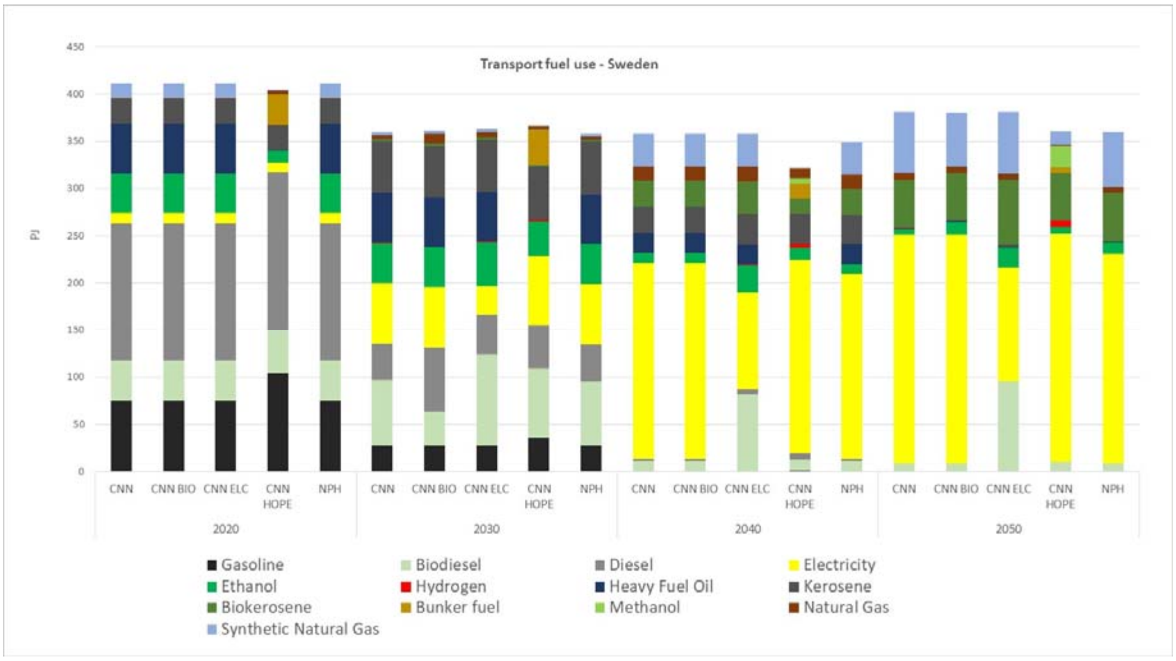

Figure 3-2: Cost-effective fuel choices in the Swedish transport sector in the assessed scenarios when using the ON-TIMES model. For scenario descriptions of the CNN, CNN BIO, CNN ELC, CNN HOPE and NPH scenario see the text. Synthetic natural gas (methane) is based on hydrogen or bioenergy, sometimes combined with carbon capture and storage, CCS.

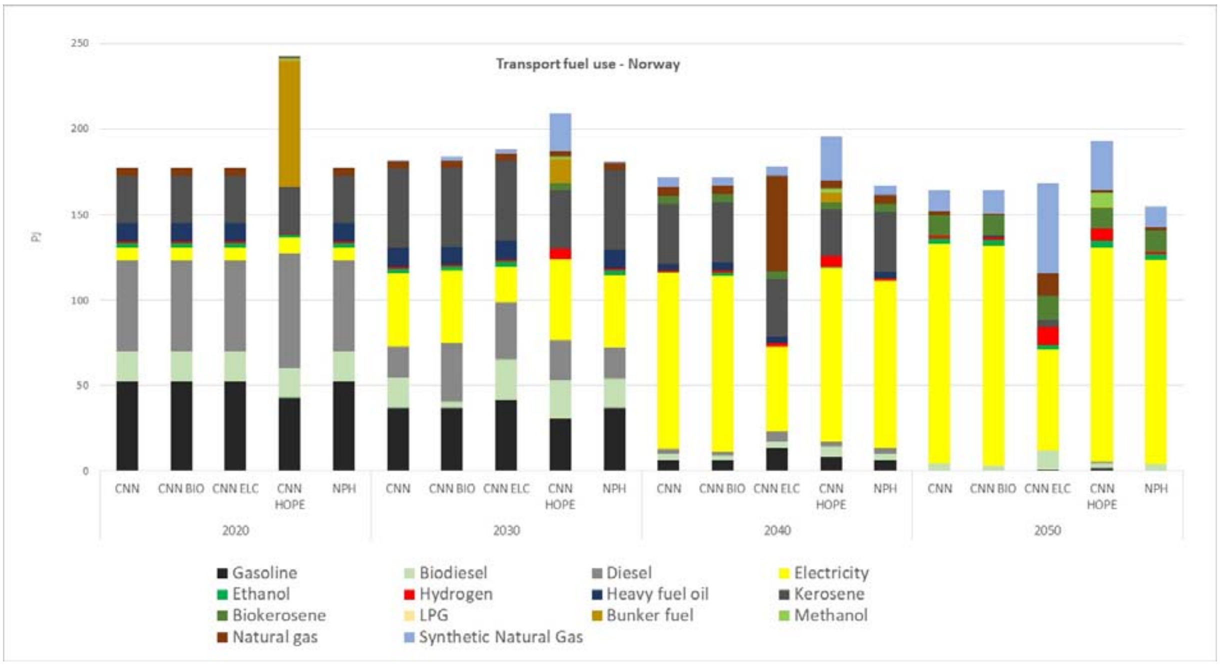

Figure 3-3: Cost-effective fuel choices in the Norwegian transport sector in the assessed scenarios when using the ON-TIMES model. For scenario descriptions of the CNN, CNN BIO, CNN ELC, CNN HOPE and NPH scenario see the text. Synthetic natural gas (methane) is based on hydrogen or bioenergy, sometimes combined with carbon capture and storage, CCS. LPG represent Liquefied petroleum gas.

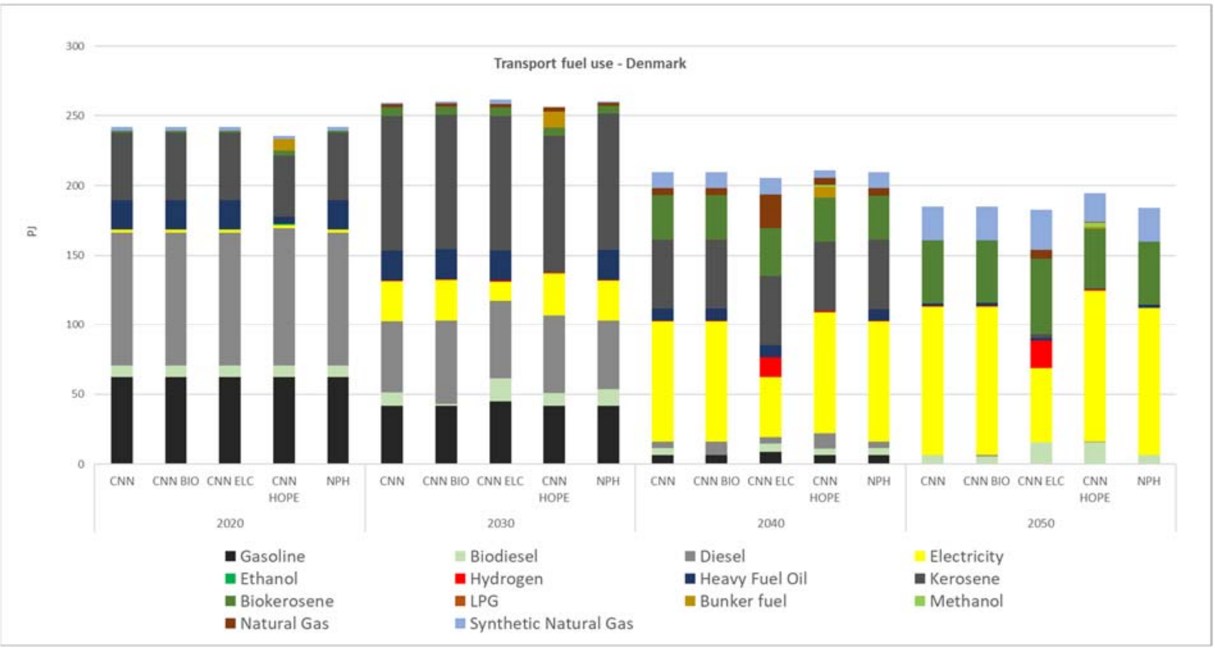

Figure 3-4: Cost-effective fuel choices in the Danish transport sector in the assessed scenarios for Denmark. For scenario descriptions of the CNN, CNN BIO, CNN ELC, CNN HOPE and NPH scenario see the text. Synthetic natural gas (methane) is based on hydrogen or bioenergy, sometimes combined with carbon capture and storage, CCS. LPG represent Liquefied petroleum gas.

Development of a modelling tool for linking and transferring data between the ON-TIMES model and the GAINS model

The initial version of the digital tool for transferring data between the TIMES-Nordic Model and GAINS model was adapted and improved for the ON-TIMES model and first tested using an existing base case scenario (the CNN scenario). The tool enables analysis of the interaction between the environmental efficiency of the transportation systems and the overall energy system. The output from ON-TIMES in terms of transport related energy carriers, technologies, vehicles, transport work etc. was used in GAINS to assess the effects on emissions of e.g., new technology, model shifts, or fuel shifts. The GAINS model also includes values for abatement costs for reducing emissions to air, either through treatment technology, new technology, or through the exchange of materials, fuels, or methods.

The energy scenario output from ON-TIMES consists of a set of categories that represent combinations of fuel types and fuel technologies, like the structure of the GAINS model. However, there are significant differences in the categorisation systems between the two models, making the ON-TIMES results not directly interpretable for GAINS. To address this, the tool utilises a complex matching system to transfer, aggregate or divide values, or a combination of these methods. In some cases, there is a one-to-one relationship between the categories, but more often there are several-to-one, one-to-several, or several-to-several relationships. The IVL-developed tool is designed to automatically recalculate the energy values from ON-TIMES and allocate them into the corresponding GAINS input categories.

An **emission scenario** in GAINS is created through a combination of these three data categories:

- Activity pathways
- Emission vectors
- Control strategies

Every combination of the three determines the level of actual emissions. The data are specific to each GAINS region (most often a country). Beyond these region-specific parameters, general (global) parameters also need to be defined, which are called scenario meta data. Emissions scenarios in GAINS combine region-specific activities with sets of emission factors and cost coefficients, which are called in GAINS "emission vectors". In addition, control measures laid down in the GAINS control strategies to be applied. This function is used to view the structure of an emission scenario.

In GAINS, we do not utilise the complete range of emission scenarios. Instead, we incorporate energy scenarios generated by ON-TIMES as the primary input. These energy/fuel values are combined with emission factors provided by the GAINS model. Additionally, at the end of the calculations, we apply various control strategies from the GAINS model that correspond to specific emission scenarios within the model.

The GAINS model includes different types of predefined emission scenarios, including those that explore the potential for environmental improvements through emission control measures not yet included in current legislation. In our project, we examined a few emission scenarios. The names of these scenarios offer insights into their respective types and short explanations follow:

- **Baseline scenario**: This scenario assumes the efficient enforcement of existing legislation without additional actions. It encompasses measures that have already been agreed upon and integrated into current and planned legislation. Baseline scenarios in GAINS are regularly updated to incorporate new knowledge.

- **MTFR (Maximum Technical Feasible Reduction):** This scenario investigates the inclusion of structural and behavioural changes, likely revealing more cost-effective approaches to achieving environmental targets. Moreover, it demonstrates the possibility of reaching targets lower than the MTR.
- **MFR (Maximum Feasible Reduction):** This scenario represents the maximum feasible implementation of the most efficient emission reduction measures currently available on the market.

To focus on the impact on emissions of air pollution of various scenarios based on energy system modelling, only the baseline plus MTRF scenario is presented in this report.

Assessment of the potential impact of different decarbonisation scenarios in the Nordic transport sectors on the most common air pollution emissions (NO_x and particulate matter)

The impact on selected emissions of air pollution (focusing on NO_x and particulate matter) of the different decarbonisation scenarios representing different policy initiatives for reducing GHG emissions in the transport sector are assessed to validate the transfer tool. The focus is on exhaust emissions, i.e., emissions linked to the fuel use. Thus, emissions from for example tire wear etc. are not included.

The results for the development of air pollution in the form of NO_x emissions in the assessed scenarios for aviation, shipping, and road including rail are illustrated in Figure 3-5 for Sweden, Figure 3-6 for Norway and Figure 3-7 for Denmark. The results for 2020 are also based on the modelling and have not been validated in detail against the actual outcome. This is indicated in the figures by brighter colour for the 2020 bar.

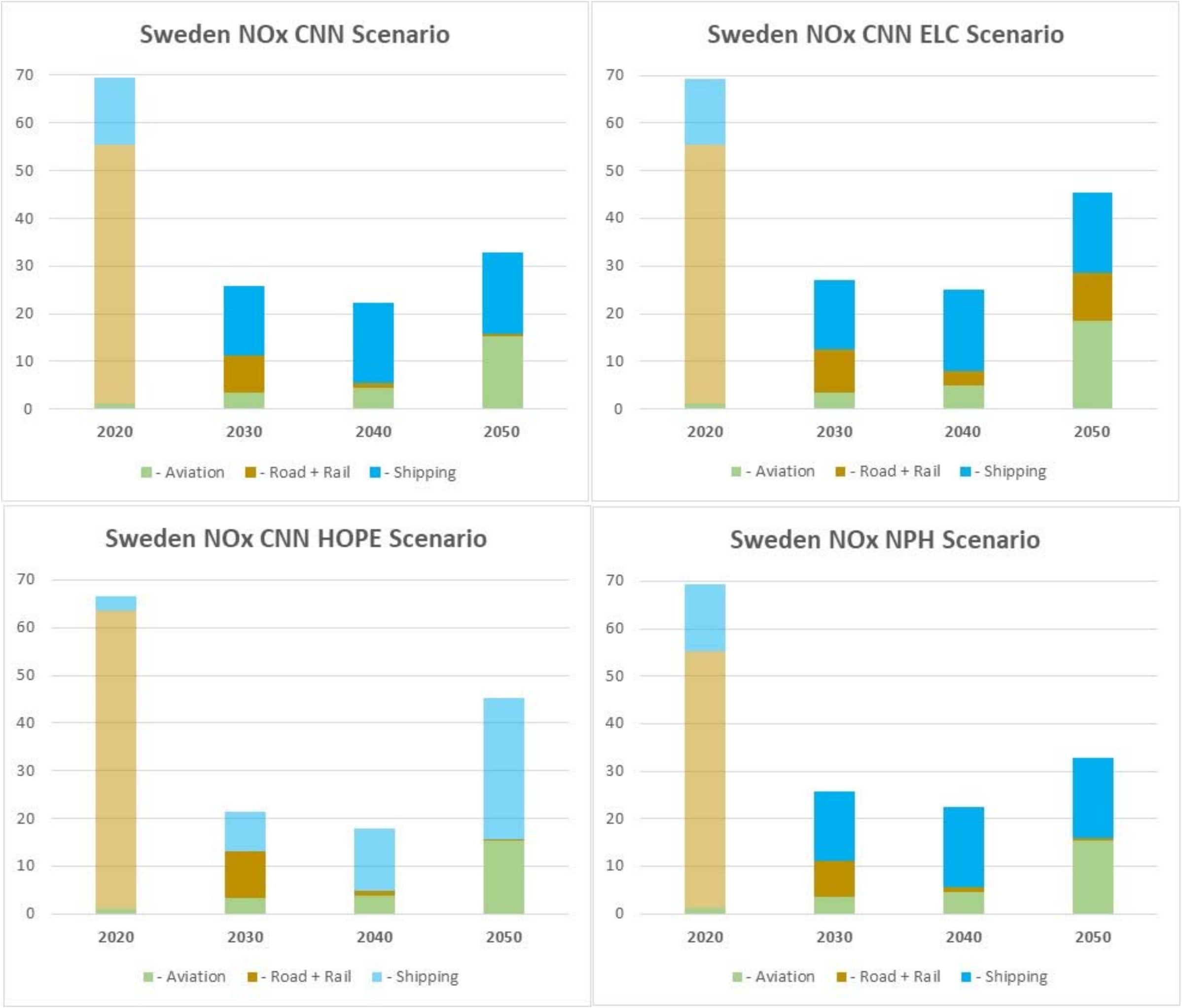

Figure 3-5: The modelled development of NO_x emissions for aviation, road transport including rail, and shipping in Sweden in the CNN, CNN+less electrification (CNN ELC), CNN HOPE, and NPH scenarios. For scenario descriptions of the CNN, CNN ELC, CNN HOPE and NPH scenarios, see the text.

Figure 3-6: The modelled development of NO_x for aviation, road transport including rail, and shipping in Norway in the CNN, CNN+less electrification (CNN ELC), CNN HOPE, and NPH scenarios. For scenario descriptions of the CNN, CNN ELC, CNN HOPE and NPH scenarios, see the text.

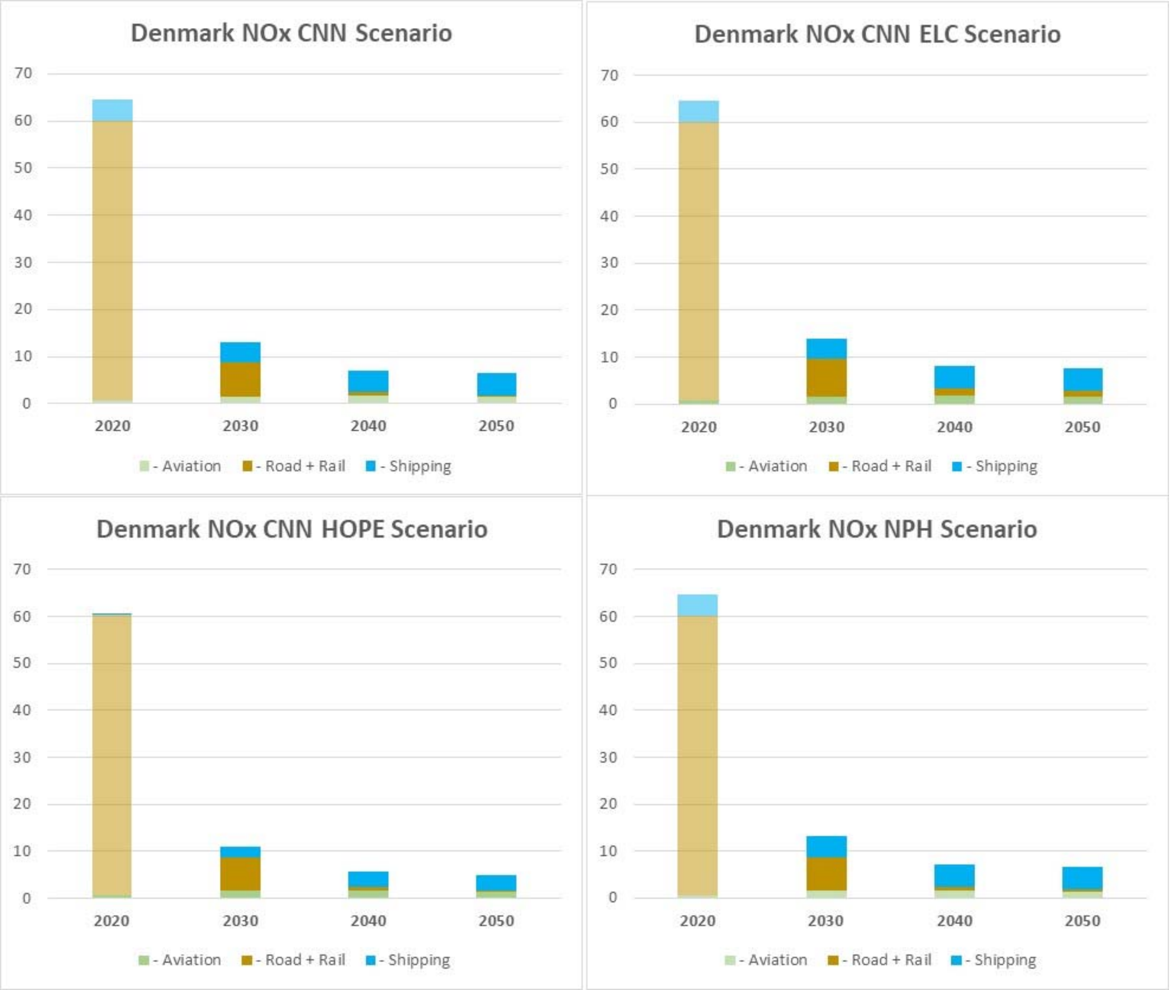

Figure 3-7: The modelled development of NO_x for aviation, road transport including rail and shipping in Denmark in the CNN, CNN+less electrification, CNN HOPE, and NPH scenarios. For scenario descriptions of the CNN, CNN ELC, CNN HOPE and NPH scenarios, see the text.

As shown in Figure 3-5, Figure 3-6 and Figure 3-7, the rapid electrification in the road transport sector in the CNN, CNN HOPE and NPH scenarios leads to lower NO_x emissions compared to 2020 in these scenarios but also compared to the CNN+less electrification scenario with a lower electrification rate (for 2040 and 2050). However, as the road transport sector is also electrified to some extent in the latter scenario, the NO_x emissions are reduced in this scenario as well but to a lesser extent. On the other hand, varying levels of biofuels will not influence air pollution in the assessed Nordic countries to a major extent as they mainly replace fossil fuels which have similar emissions of NO_x. Increased use of hydrogen will also lead to reductions in terms of NO_x emissions (as is illustrated for shipping in the CNN HOPE scenario for 2030 and 2040 compared to the other scenarios). The reason for the increase in NO_x emissions in 2050 in Norway and Sweden in the CNN HOPE scenario compared to the CNN scenario is due to the assumed increased demand for shipping and thereby fuel use in 2050 in the Nordic Clean Energy Scenario project. The assumptions in the HOPE project require further investigation but are outside the scope of this project. The stronger reduction in NO_x emissions in Denmark in all assessed scenarios compared to 2020 is due to the assumed relatively rapid decrease in transport fuel demand in Denmark.

The results for the development of air pollution in the form of emissions of particulate matter in the assessed scenarios for aviation, shipping, and road including rail are presented in Figure 3-8 for Sweden, Figure 3-9 for Norway and Figure 3-10 for Denmark. The results for 2020 are also based on the modelling and have not been validated in detail against the actual outcome. This is indicated in the figures by brighter colour for the 2020 bar.

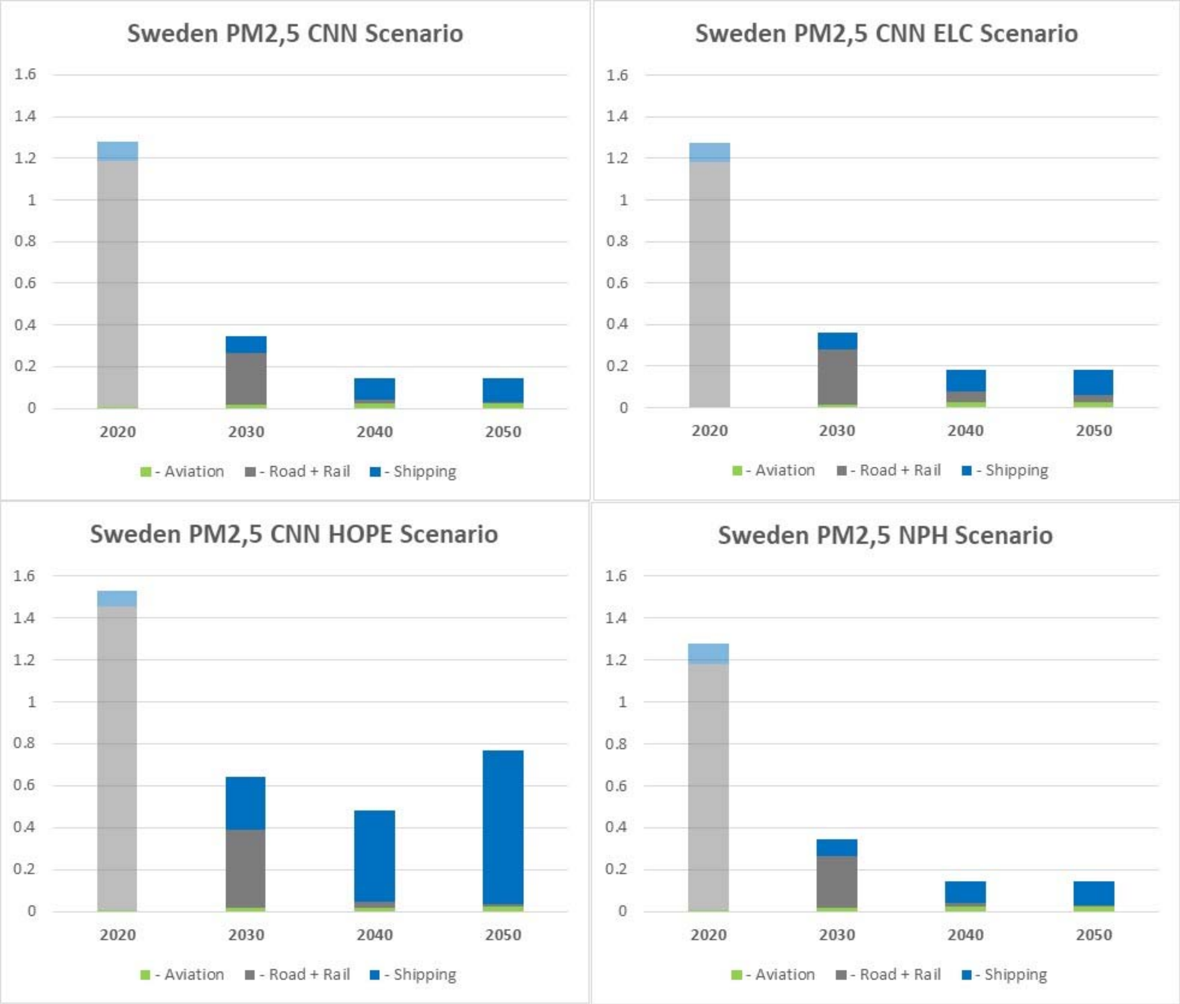

Figure 3-8: The modelled development of particles (PM2.5) for aviation, road transport including rail and shipping in Sweden in the CNN, CNN+less electrification (CNN ELC), CNN HOPE, and NPH scenarios. For scenario descriptions of the CNN, CNN ELC, CNN HOPE and NPH scenarios, see the text.

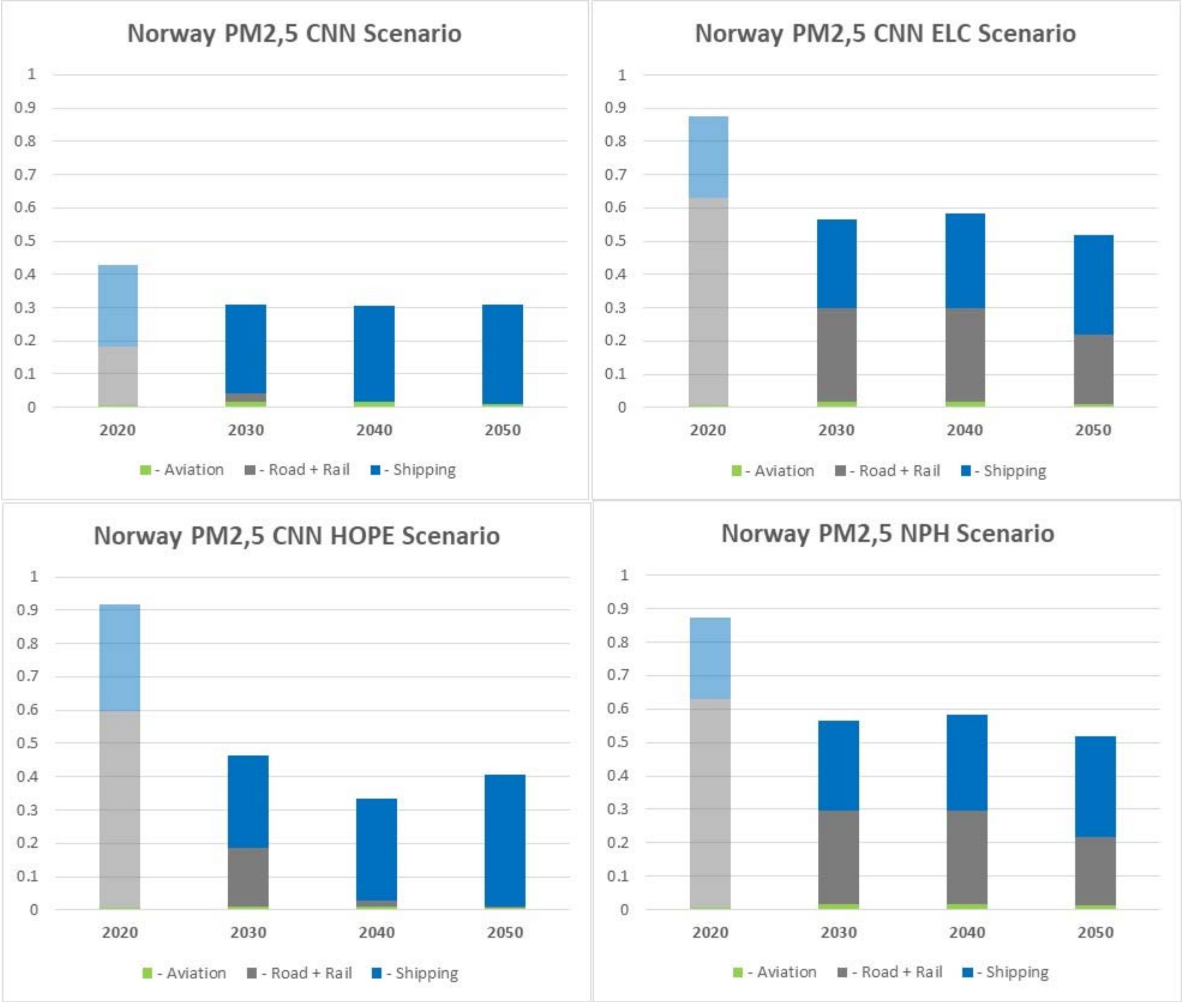

Figure 3-9: The modelled development of particles (PM2.5) for aviation, road transport including rail and shipping in Norway in the CNN, CNN+less electrification (CNN ELC), CNN HOPE, and NPH scenarios. For scenario descriptions of the CNN, CNN ELC, CNN HOPE and NPH scenarios, see the text.

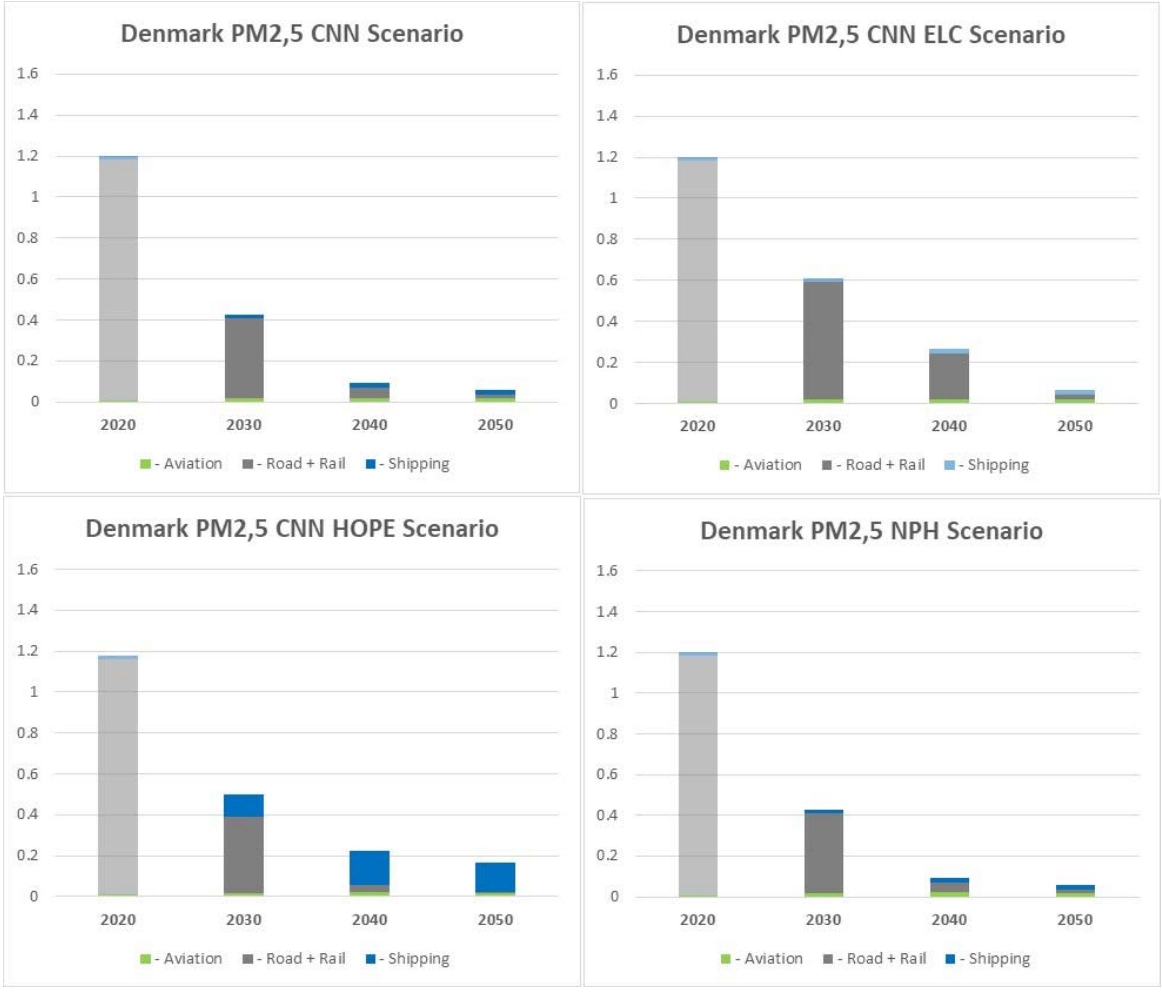

Figure 3-10: The modelled development of particles (PM2.5) for aviation, road transport including rail and shipping in Denmark in the CNN, CNN+less electrification, CNN HOPE, and NPH scenarios. For scenario descriptions of the CNN, CNN ELC, CNN HOPE and NPH scenarios, see the text.

The rapid electrification of the road transport sector also leads to lower particle emissions (in the form of PM2.5) by time for all scenarios but also compared to the scenarios with a lower electrification rate (mainly CNN+less electrification scenario but for Norway also in the NPH scenario). The impact of the electrification rate is particularly evident in the Norwegian case. As expected, reductions in energy transport demand leads to lower emissions of NO_x and PM. The increase in particles in the CNN HOPE scenario remains to be confirmed in further studies (the scenario output and transfer of data need to be checked in more detail). The increase in particles in 2050 compared to 2040 in the CNN HOPE scenario is due to the assumed increase in fuel demand for shipping based on the Nordic Clean Energy Scenario project. The assumptions in the HOPE project require further investigation but are outside the scope of this project.

The NO_x emissions in Sweden for the road sector in 2020 found in the modelling match relatively well with the reported emissions of NO_x from road transport in Sweden[1]. A comparison of the

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[1] https://www.naturvardsverket.se/data-och-statistik/luft/utslapp/utslapp-av-kvaveoxider-till-luft-fran-vagtransporter/

modelled NO_x emissions for aviation and shipping for Sweden with the reported emissions of NO_x from the domestic use of these transport modes also confirms that the levels are reasonable. Emissions of particles are much more difficult to compare with national statistics due to definition and delimitation issues. Thus, the estimates of particle emissions with the presented approach need to be further assessed in coming projects to confirm that they represent realistic levels.

To illustrate the impact on emissions from a broader energy system context, it is important to include transport-related emissions from other energy sectors (e.g., from electricity production for electric vehicles) not included in this assessment focusing solely on the transport sector. Emissions linked to electricity production occur in a different environment and with potentially less exposure than direct emissions from transport.

Informing energy system analysis

The project provides an initial assessment about the extent to which emissions other than GHG, i.e. emissions of air pollution, are interesting to address in Nordic energy system model assessments. It also provides an example of how the impact of air pollution linked to various scenarios from Nordic energy systems modelling can be assessed. This information is shared to other energy system modellers in the Nordic region mainly via this report and the final workshop of the project. A policy brief summarising the findings will also be published during the autumn of 2023 to further disseminate the findings.

3.3. Emerging fuels and technology options in the aviation sector

The explorative analysis of emerging fuels and technology options in the aviation sector is carried out by use and further development of the IFE-TIMES-Norway model. The analysis covers different aspects, including the following:

Scenarios and decarbonisation pathways for the Norwegian energy system and transport sector

The analysis conducted built on previous work and assumptions used to assess different societal, political, and technological developments aiming towards a low-carbon future energy system in Norway. The scenarios used in the analysis take as a starting point the scenarios developed under the Norwegian Centre for Energy Transition Strategies (FME NTRANS) and present further developments to address IFE's research objectives presented in Section 1.3. Furthermore, based on discussions with project partners and bilateral meetings, the scope of scenarios was narrowed to include similar storylines and coherent assumptions regarding the development of different demands, measures, and the availability of resources and technologies. As a result of this exchange, the Radical scenario from FME NTRANS was selected to illustrate a transition pathway where there is a high degree of both societal and technological change in line with the assumptions presented in the Carbon Neutral scenarios from the ON-TIMES model, developed for the Nordic Clean Energy Scenarios project. Further description of the Radical scenario, and other NTRANS scenarios, is provided in Appendix A Scenario overview.

Aligning modelling improvements to cover new technologies and fuel pathways

The IFE-TIMES-Norway model was used to carry the analysis regarding emerging fuels and technology options in the domestic aviation sector, illustrating potential options from a Norwegian perspective. In previous versions of the model, certain technologies had not yet been included which otherwise provide alternative low-carbon options to cover transport demands; for example, the use of synthetic fuels or direct air capture options. These options, however, are available in other proposed scenarios and their underlying models covering the Nordics, including Norway, as is the case with the ON-TIMES model. More fundamentally, ongoing industrial activity and plans aim to commercially develop said options in the near-future [11], [12]. Consequently, the IFE-TIMES-Norway model underwent further development to align with the ON-TIMES models assumptions and provide a better representation of these future options available in the scenario modelling of the transport sector.

Assessing impacts of options

The results from the model illustrate the potential uptake of new alternative green fuels towards 2050. Moreover, the results show that electrofuels in aircraft can play a role in the future decarbonisation of domestic aviation in Norway by replacing part of the remaining fossil consumption. On a broader system level, the inclusion of these options also facilitates the use of renewable electricity and hydrogen, providing an additional balancing option for fluctuating renewable production, as well as creating additional demands for a prospectively emerging hydrogen market. However, the production costs of these fuels and upstream processes, like direct air capture of CO_2, can restrict both how early and to what extent synthetic fuels start playing a role in the energy transition. The characterisation of these technologies in the model also adds a layer of uncertainty, since further technological maturity will dictate how the investment costs of these options will actually develop and how these could be deployed to cover part of the future market share for sustainable aviation fuels. Further in-depth assessments of these options are therefore needed to provide insight into the future role of synthetic fuels and carbon capture and utilisation options from both the Nordic and European perspectives.

The following results aim to explore potential alternative green fuel pathways for decarbonising the aviation sector. As mentioned, the IFE-TIMES-Norway model was updated and expanded in this project so that synthetic jet fuels were also represented to cover part of the projected demands of Norway's domestic aviation sector. In addition, the model was also updated to consider additional detail of other potential aviation fuel replacements. Namely, a more gradual rollout is now considered for hydrogen-powered aircrafts - which are expected to first become commercially available by 2035. In addition, a representation of electrofuels has also been incorporated in the model as an additional fuel replacement option. To illustrate the above-mentioned considerations, the Radical scenario from FME NTRANS was used and adapted accordingly. The results of considering these different assumptions are presented in Figure 3-11.

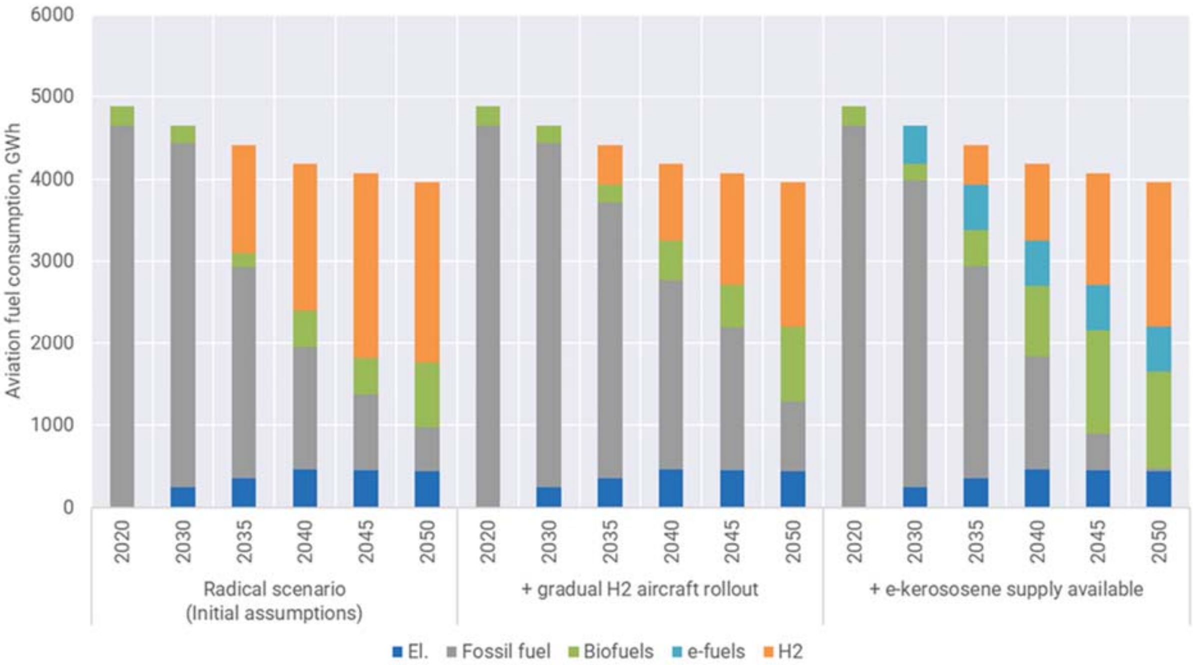


Figure 3-11: Projected aviation fuel consumption for the Radical scenario, considering base assumption, and additional assumption on H_2 aircraft rollout and synthetic fuel availability.

As illustrated in Figure 3-11, the base assumptions portray a pathway where the adoption of hydrogen in aviation plays a prominent role from 2035 to 2050, representing about a 50% share of the aviation fuel consumption in the latter year. Under these assumptions, biofuel consumption as well as electric-powered aviation also increase albeit not as substantially. Meanwhile, the shares of fossil fuels in aviation are estimated to be reduced from 90% in 2030 to about 13% by 2050. As a further step in this project, conservative assumptions on the availability of hydrogen-powered aircrafts have been introduced to capture expectations regarding hydrogen-based aircrafts becoming commercially available by 2035. This assumption limits the rollout of hydrogen as a fuel in the aviation sector, leading to a share of about 44% by 2050, and a higher contribution from fossil fuels covering about 21% of the aviation fuel consumption by the same year. Introducing this limitation also leads to an increase of the expected biofuel consumption.

Building on these assumptions, the model was further developed to include synthetic kerosene as a potential fuel replacement to the current fossil fuel supply in the sector. This means introducing new additional processes in the model, such as direct air capture (DAC) and Fischer-Tropsch synthesis to represent the synthetic fuel production plants. The addition of synthetic fuels as an available fuel supply option results in a progressive uptake, initially covering about 10% of the total aviation fuel shares to approximately 14% by 2050. In this updated scenario, hydrogen shows similar shares in the initial stages increasing to about 44% by 2050, while biofuels are expected to cover about a third of the fuel consumption by the same year. For all three cases of the scenario, the proportion of electricity-powered aircrafts remain fixed, covering up to about 11% of the aviation energy demands by 2050.

Introducing these fuel replacements has an impact on the future decarbonisation of the aviation sector, as illustrated in Figure 3-12. As shown in the figure, the CO_2 emissions are relatively similar for all cases up to the year 2030. By 2035, the scenario becomes more sensitive to assumptions regarding fuel options. For example, looking at the updated scenario with a more gradual rollout of hydrogen aircrafts, relatively higher emission levels are in place due to the larger shares of fossil fuels for aviation left in the sector. Meanwhile, in the updated scenario where synthetic fuels are in place, a relatively lower level of emission is seen already in 2030 and onwards due to the replacements with synthetic fuels already covering aviation demands.

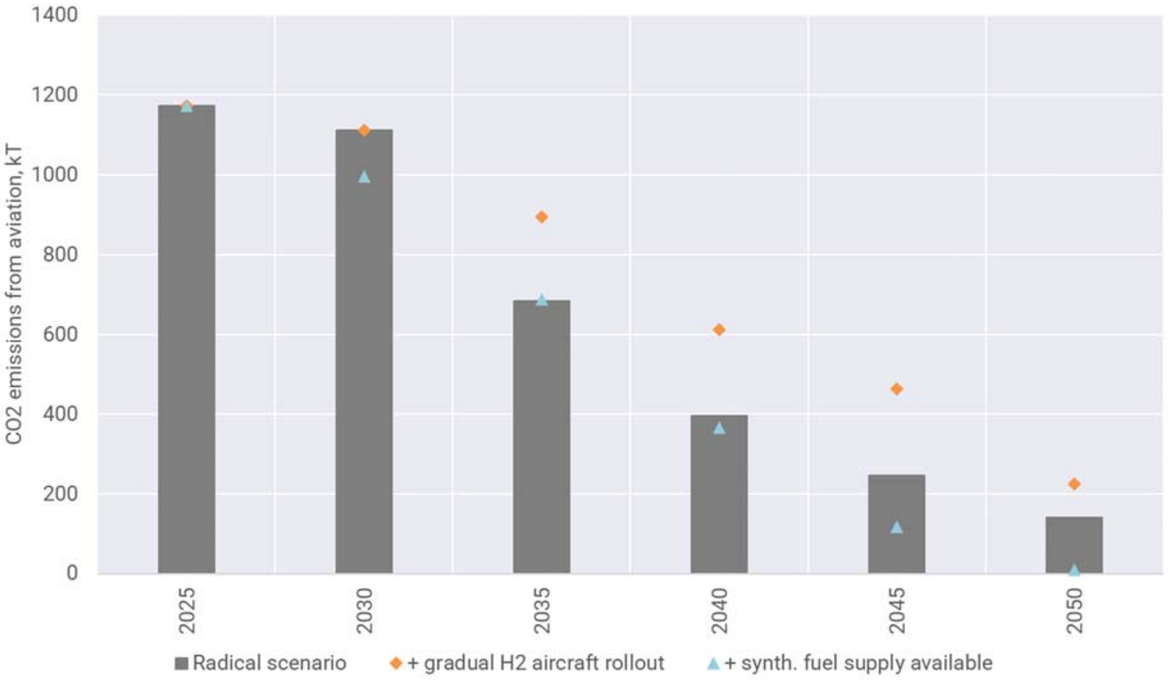


Figure 3-12: Projected CO_2 emissions from aviation

3.4. Qualitative methods provide alternative insights into transport futures

The complexity of modern policymaking, coupled with the challenge of addressing critical issues like climate change, have prompted a reconsideration of how decision-making processes should take place in the twenty-first century. Within this context, the OECD has presented evidence endorsing the potency of citizen participation, or deliberative democracy, in shaping public decisions. Such participation is posited not only to yield better policies but also to fortify democratic foundations [40].

Delving deeper into the rationale presented by the OECD, the analysis aimed to uncover opportunities or improving energy consumption projections within the transportation sector. The primary objective was to compare recommendations emerging from two distinct cases of deliberative democratic processes with the foundational assumptions underpinning the Danish Energy Agency's projections of future Danish energy consumption within the transportation sector.

In particular, the following two questions were posed and answered:

1. What assumptions regarding energy consumption does the Danish Energy Agency use when projecting Danish transport development?
2. How do recommendations for the transportation sector generated via deliberative democratic processes compare to the energy consumption assumptions used by the Danish Energy Agency when projecting Danish transport development?

What assumptions regarding energy consumption does the Danish Energy Agency use when projecting Danish transport development?

The projection of energy consumption in the Danish transportation sector is presented in the Climate Status and Outlook; a yearly publication by the Ministry of Climate, Energy and Utilities that provides a historical account, status and projections of energy consumption (among other things) over a period of 10-15 years in a "Frozen policy"-scenario.

The Climate Status and Outlook 2022 (hereafter: CSO22) in particular, projects energy consumption in the Danish transportation sector until 2035, only taking into account regulations and political measures decided upon before January 1st, 2022 [41].

The projection is carried out using a bottom-up approach in the Danish Energy Agency's transport model FREM, which covers the transport categories of Road transport, Rail transport, Aviation, Shipping and Other transport (recreational vessels and military transport vehicles). The approach and level of detail vary among the categories, with the highest focus generally placed on categories with the largest energy consumptions [42].

The calculation of energy consumption is generally based on assumptions regarding traffic volume (demand for transport) and the composition of the vehicle fleet in terms of technologies and fuels. The assumptions are characterised by a strong tie to historic trends such that e.g. a historical increase in road transport is reflected in a projected increase, as well as a 'rational economic man'-approach in which actors are assumed to respond economically rationally to market conditions.

How do recommendations for the transportation sector generated via deliberative democratic processes compare to the assumptions regarding energy consumption used by the Danish Energy Agency when projecting Danish transport development?

Deliberative democracy is "the wider political theory that claims that political decisions should be a result of fair and reasonable discussion among citizens" [40].

As a methodology, deliberative democracy is characterised by a process in which citizens exchange and deliberate on informed arguments with the purpose of coming to a consensus on what action or policy will best produce a specific public good [43]. Deliberative processes are usually carried out with a mandate to inform political decision-making.

The Danish Citizens' Assembly on climate as well as the Danish Energy Agency's Vision workshop on Future Mobility were chosen as cases of deliberative democracy for this specific study.

The Citizens' assembly consists of 99 members selected randomly by Danmarks Statistik to represent as best as possible the Danish population, tasked with debating citizen-centric dilemmas associated with the green transition and providing recommendations for climate initiatives [44]. So far, two sessions of the assembly have been held. The first session took place from the autumn of 2020 to the beginning of 2021 [44] and resulted in 119 recommendations for the green transition covering the topics of adult education, involvement and behaviour, financing and taxes, agriculture, land and resources, transportation, and technology in the landscape [45]. The second session was held at the end of 2021 and concluded with 73 recommendations on the topics of behaviour, consumption, agriculture, buildings, transportation, and energy supply [46]. In the analysis at hand, the focus is on the recommendations given on transport.

In October 2021, the Danish Energy Agency facilitated a workshop on future mobility with the title 'Sustainable transport in the future' (hereafter: "VW"). The purpose of the workshop was to uncover blind spots in the Danish Energy Agency's understanding of the energy system and the underlying developments and behavioural aspects of mobility in order to inform both better scenario building and point to options for new analysis work at the Danish Energy Agency. The workshop was carried out in one day with the participation of ten Danish mobility experts from universities, NGOs and other institutions that are not normally part of the reference groups that the Danish Energy Agency use when formulating model assumptions. During the VW, the participants completed a combination of individual exercises and group exercises, which sought to allow the participants to imagine a Danish transport system in 2050, as they preferred it. The goal was to gather unexpected ideas and connections, rather than creating complete scenarios. The results from the workshop have not been published before.

The term 'products' is used as a collective term for the CSO22, the CA, and the VW.

Analytical framework

To systematically explore the variances between the CSO22 assumptions and the recommendations of the CA and the VW, an analytical framework consisting of four theoretical approaches was created for a comprehensive understanding of the following dimensions:

- Perspective (*Futures studies*)
- Orientation (*Systems theory*)
- Change possibilities (*the A-S-I approach to transport demand*)
- Instruments for change making (*Policy instruments*).

Futures studies is the systematic study of futures and is concerned with the longer term [47]. Futures studies can be classified based on the three approaches of thinking about the future: 1) Possible futures (What might happen?), 2) probable futures (What is most likely to happen?) and 3) preferable futures (What is preferred to happen?). Probable futures and preferred futures are both also possible futures [48].

Systems theory recognises the interconnections and interdependencies between parts and wholes, embracing both holism and atomism. It acknowledges the importance of understanding the whole system as well as its constituent parts. It also emphasises the hierarchical structure of systems, including subsystems within larger systems [49]. As such, the use of Systems theory can help illuminate whether other systems than the transport system is considered, which parts of the transport system is considered and to what level of detail.

The A-S-I ("Avoid", "Shift", "Improve") approach to transport demand *deals with aspects of demand itself regarding ways to reduce CO_2 emissions through the avenues of avoidance, shift and improvement using "Avoid"-, "Shift"- and "Improve"-tactics. "Avoid"-tactics seek to avoid or reduce travel through improved transport system efficiency. "Shift"-tactics are concerned with improved trip efficiency through the exchange of one transport mode with another more energy efficient mode of transport. "Improve"-tactics relate to improved vehicle efficiency through the use of less polluting fuel or improved energy efficiency [50]. In their latest report, the IPCC concluded that* "Demand-side mitigation and new ways of providing services can help avoid, shift, and improve final service demand. Rapid and deep changes in demand make it easier for every sector to reduce greenhouse gas (GHG) emissions in the short and medium term (high confidence)" *[51].*

Policy instruments are tools available to a government that wants to bring about changes in society by influencing *the behaviour of citizens and businesses. Vedung (1998) distinguishes between three such tools, or so-called 'policy instruments': regulatory (imposition and prohibition), economic (positive and negative), and informative (e.g. campaigns) policy instruments [52].*

Results

By systematically applying the aforementioned analytical framework, the analysis found several variances and convergences among the assumptions of the CSO22 and the recommendations of the CA and the VW, as seen below.

Futures studies

The analysis found that the CSO22 and the VW are both (possible) futures studies and can further be comprehended as a probable futures study and a preferred futures study, respectively (see Table 3-1). The CA can't completely be classified as a futures study as it doesn't represent a full picture of a future on system level but deals with recommendations case by case.

Table 3-1: Mapping CSO22. The CA, and the VW as possible, probable or preferred future studies.

	Possible futures study	Probable futures study	Preferred futures study
CSO22	X	X	
CA	(X)	(X)	(X)
VW	X		X

CSO22 falls in the probable futures study-category as it starts from the present and is centred on forecasting trends based on historical data and the practice of business as usual. The VW can be classified as a preferred futures study due to its focus on the attainment of desirable futures and the use of back casting methods. Although the CA is not a futures studies as such, it compares to the probable futures studies (and therefore to CSO22) by starting from the present rather than starting from the future, and to the preferred futures studies (and therefore the VW) by applying a normative approach rather than a descriptive approach.

Systems theory

Viewing the assumptions/recommendations of the CSO22, the CA the VW workshop from the backdrop of Systems theory, the analysis found that CSO22 differs from the CA and the VW by being less detailed in breadth (system view) and to some extent more detailed in depth (system component view). The transport assumptions used in CSO22 all refer to the transport system as an enclosed system, while the recommendations from the CA and the VW also consider other systems such as *Environment*, *Morality*, *Health*, and *Lifestyle*, that might influence the preference and behaviour concerning transport choices.

Examples of recommendations from the CA on related systems such as *Environment* and *Morality* are "All gasoline and diesel-powered distribution vehicles within major cities should be subject to taxation based on environmental labels by 2030" and "Charging infrastructure should be expanded in a way that ensures equal accessibility", respectively. Examples of recommendations from the VW on *Flexible lifestyle* and *Health* are "Flexible work conditions lead to less transportation, such as avoiding commuting through remote work and online meetings" and "Health and attractive surroundings have become significant reasons for more cycling and walking, which improves public health and benefits the economy", respectively. Table 3-2 lists the number of assumptions/recommendations from the three products under four systems in the context of transport.

Table 3-2: Number of CSO22 assumptions and CA/VW recommendations related to the systems of Environment, Flexible lifestyle, Morality, and Health under the context of transport.

	Environment	Flexible lifestyle	Morality	Health
CSO22	0	0	0	0
CA	10	0	5	0
VW	4	2	1	2

NB.: The number of assumptions/recommendations is used to show where the focus of the individual product has been.

While the scopes of the CA and the VW are broader in terms of the systems included in transport development, the CSO22's scope is broader regarding the inclusion of different transport modes, and specification of energy/fuel type; by both including a larger amount of distinct transport modes and specifying their energy/fuel type to a larger extent. However, CSO22 is less detailed than the CA and the VW when it comes to specifying how the transport modes are to be utilised in practice, for instance when and why trips take place, and who the users of different transport modes are or should be.

The A-S-I approach to transport demand

Applying the framework of the A-S-I approach to transport demand, the analysis found that CSO22's assumptions differ widely from the recommendations of both the CA and the VW.

Of the CSO22 assumptions that can be understood through the A-S-I framework, all of them can be categorised as having to do with the avenue of Improve and none of them having to do with the Avoid and Shift categories, specifically focusing on the topics of: *Improved energy efficiency*, *Electrification of transportation*, and *Access to charging infrastructure*. On the other hand, the CA and the VW assumptions that fall under the A-S-I framework are distributed across all three avenues of Avoid, Shift and Improve. Generally, Avoid-tactics include all measures that result in less transport altogether, e.g. through land-use planning, working from home rather than commuting, vacationing in your home country rather than flying overseas and so on.

An example of an "Avoid"-tactic from the VW is "Flexible work conditions lead to less transportation, such as avoiding commuting through remote work and online meetings." Both the VW and the CA recommend car free zones in cities, which is categorised here as an avoidance tactic since people living in the area might tend to prefer local shops and cultural activities over more distant services.

Generally, Shift-tactics include shifting transport mode from polluting to less polluting, from individual motorised to public transport or shifting from car to cycling. Examples of Shift-tactics from the CA are "There should be an economic incentive to use biofuels, electricity, or PtX. This way, a portion of the transport currently carried out by trucks will be shifted to, for example, trains, electric trucks, or less polluting methods" and "Continue the expansion and improvement of the existing path and road network to promote cycling", while the VW suggested "Private car usage is taxed through road pricing" (implying a shift to other transport modes such as public or shared transport), and "Fully electric night trains across Europe replace some air travel, both for leisure and business trips".

Examples of Improve-tactics from the CSO22 are "… expected improvement in energy efficiency through advancements in aircraft technology…" and "It is expected that several domestic ferries will be electrified…". Examples from the CA are "Minibuses should be used where relevant, instead of large half-empty buses" and "Public transport should run on electricity or hydrogen fuel as it should serve as a role model for electrification.". The VW suggested "There is a high tax on aviation, and air travel is primarily for long-distance trips and operates on e-jet fuel." and "By 2050, the car fleet consists exclusively of electric vehicles." Table 3-3 lists the number of assumptions and recommendations related to the A-S-I approach to transport demand.

Table 3-3: Number of CSO22 assumptions and CA/VW recommendations related to the avenues of Avoid, Shift and Improve.

	Avoid	Shift	Improve
CSO22	0	0	18
CA	2	11	17
VW	5	6	6

NB.: The number of assumptions/recommendations is used to show where the focus of the individual product has been.

Policy instruments

Looking through the lens of the policy instrument-typology (Regulatory, economic and informative policy instruments), the analysis found that CSO22's assumptions compare to the recommendations of the CA and the VW, especially the latter.

Both the CSO22, the CA and the VW have assumptions/recommendations that fall under the categories of Regulatory and Economic policy instruments, having to do with the topic of: *EU-regulation, public transportation tenders, Legal requirements, Exclusions, and Limitations* (Regulatory policy instruments), and *Tax incentives, Funding of initiatives, Economic incentives, Affordable public transportation, Points earning mechanisms, Fees*, and *Taxes* (Economic policy instruments). Only the CA has recommendations that relate to the informative policy instruments. These have to do with the topics of *Labelling systems, Campaigns*, and *Information tools.*

Qualitative research performed includes a comparative study by the DEA of the foundational assumptions underpinning projections of future energy consumption and recommendations emerging from deliberative democratic processes.

Conclusion

The analysis both elucidated characteristics of the CSO22 assumptions concerning future Danish energy consumption in the transportation sector, and contributed to understanding the CSO22 assumptions in relation to the recommendations of the CA and the VW with respect to perspective, orientation, change possibilities, and instruments for change making.

The CSO22, the CA, and the VW all offer unique dimensions to the discourse surrounding future energy consumption in the Danish transportation sector, each possessing its own respective strengths and weaknesses. While it may not be feasible or even desirable to integrate their approaches due to their disparities, it is valuable to consider how the approach to projecting energy consumption in the transportation sector could be influenced by or complemented with insights from deliberative democratic processes.

3.5. Proposed methodology on considering critical raw materials (CRMs) in energy system modelling

This section will explain the methodology developed to take critical raw materials into account in energy system models. The work is intended to be implemented in the high spatial and temporal resolution electricity system model (highRES), but also to create a methodology which potentially could be applied in other models as well. As described in Section 2.7 highRES is a linear optimisation model.

As we have seen so far in the discussion on the future electric transport demand, the expected increase in the deployment of electric vehicles is substantial. With the rising demand for electric vehicles comes an increasing need for raw materials. Batteries are in addition becoming increasingly important as energy storage in electricity systems relying more and more on variable renewable energy such as solar and wind. The continued access to these materials is essential to decarbonise the electricity and transport sector, which is crucial to meeting the targets of the Paris Agreement. However, there are many possible issues which could cause constraints to the supply of these materials and limit the deployment of battery technologies. The approach of this work has been to suggest a methodology on how the supply risk of raw materials can be implemented in energy system models and then identify data in the literature which quantify these issues relating to the supply of raw materials for batteries. This formed a basis for the implementation of these constraints in energy system models. The goal is for energy system models to better address sustainability, account for the feasibility of the transition, and show greater resilience against the risks associated with supply constraints.

There are several possibilities as to how one can take into account raw material supply risk in energy system models. For this work, the approach suggested is a multi-objective optimisation methodology to consider supply risk in electricity system models. The problem could be formulated as follows.

Minimise:

$$af_1(x) + (1-a)f_2(x) \qquad (3-1)$$

Where:

a is the weighting of the objective function,

$f_1(x)$ is the total investment and operational cost,

$f_2(x)$ is the total supply risk metric.

Implementing the supply risk directly in the optimisation, instead of indirectly through constraints, enables some interesting analysis. The weighting of the objective functions has been defined using only one parameter, so that the weighting of $f_2(x)$ depends on the weighting of $f_1(x)$. With this approach, we can investigate how the optimal design of the electricity system changes as we move the weight of the objective function from the economic cost and towards the supply risk.

The question then is how we would calculate this total supply risk metric. The approach is based on that we have identified some measure, let us call it RF_j (RF being short for risk factor), which quantifies the supply risk of a given material j. Knowing the risk factor alone, however, is deemed not to be sufficient to quantify the total risk of an electricity system. This is based on the fact that different technologies have different material use. So, if we want to minimise the risk associated with the use of critical materials in the energy system, the amount of raw material used must be accounted for. If M_{ij} is the amount (mass) of material j used in a technology i per capacity and CAP_i is the total installed capacity of technology i, we can formulate the total risk metric of the electricity system as follows:

$$f_2(x) = \sum_{i,j} CAP_i \cdot M_{ij} \cdot RF_j \qquad (3-2)$$

What this function does, in short, is to multiply the risk metric of a material with the total amount of this material used by the total installed capacity of a technology. This is performed and summed for every single material and technology considered. It gives the risk metric weighted by the mass of the material used summed over each technology and each material used by these technologies.

Having developed a methodology to consider the risk of critical raw materials in the optimisation, we have to look at the data that can be used in the methodology. Two works were found to be particularly interesting. These are the European Commission's Critical Raw Material list [53] and the paper by Lèbre et al., *The Social and Environmental Complexities of Extracting Energy Transition Metals* [54].The European Commission's Critical Raw Materials list quantifies the supply risk of a wide range of raw materials which are essential for several sectors, including the transport sector, for the EU. *The Social and Environmental Complexities of Extracting Energy Transition Metals* presents data quantifying the environmental, social and governance risk associated with the mining of raw materials needed for the energy transition.

3.6. Effect of transport demand on power system design in 2030 and 2050

The analysis in this section investigates how improving the spatial resolution of the electric transport demand affects the optimised power system design and the total system cost. The highRES-Norway model is run for both 2030 and 2050 with two scenarios. The first one uses a simplified approach with a flat (evenly distributed throughout the day) demand curve for electric transportation, while the other scenario distributes the electric transportation demand using a standardised electric vehicle load curve [21]. Figure 3-13 and Figure 3-14 illustrate the difference between the two cases for 2030 and 2050 respectively for a day (15th of June) in Oslo. The main difference between the two scenarios is how the load from electrified transport is distributed throughout the day. With the flat EV demand, the peak occurs earlier in the day than for the scenario with the standardised EV load curve where demand is more concentrated in the later part of the day. The aim of running the model using these different demand data is to investigate the effect it has on the results of the model, namely the total system cost and installed capacities of the different technologies, and potentially illustrate the importance of having an accurate representation of demand, from electric transportation in particular, in the model.

A larger difference between the flat and standardised EV load curve is observed for 2050 than for 2030, as seen in Figure 3-13 and Figure 3-14. It is therefore expected that the change in the optimised power system will be more prominent for the 2050 case than for 2030.

Figure 3-15 and Figure 3-16 give the results from the model runs. The figures show the installed capacities in 2030 and 2050 respectively for the different scenarios for the 1995 weather year. In the figures, "base" corresponds to the model runs using a flat demand curve for electric transport, while "improved" is the model runs with the standardised load curve for electric transport. Offshore wind is not modelled to be installed before 2030 and therefore does not appear in the 2030 results but is included in the results for 2050.

Table 3-4 lists the changes in total system cost and installed capacities of solar PV, onshore wind, offshore wind, li-ion battery and import between the scenarios. Installed capacities and changes between scenarios are not included for hydropower as the capacities for this technology is fixed and thus not affected by the changing of the temporal distribution of the electrical transportation demand. Looking at the changes in the total system cost, the cost is lower with the improved load curve than with the flat load curve in 2030, but for 2050, the total system cost increases by about three and a half percent. So, we observe a decrease in costs for 2030 but an increase for 2050. The decrease in 2030 might be explained by the solar and wind resources matching better with when the demand occurs. The increase for 2050 can be explained by the increased load creating a more substantial peak in the demand, causing greater difficulties to meet demand. This might also be the reason for the large increase in import observed in 2050 compared to 2030.

Table 3-4: Changes in model results (total system cost and installed capacities) between the base and improved electric transport demand scenarios. All entries in the table show the percentage change from the base to the improved scenario. A negative number means a decrease (in cost or capacity) and the opposite for positive numbers.

Year	Cost [%]	Solar PV [%]	Onshore wind [%]	Offshore wind [%]	Li-ion battery [%]	Import [%]
2030	-0.987	-19.435	-1.780		2.140	0.000
2050	3.546	-6.154	5.381	-1.478	12.977	16.494

We have observed no clear trend in our analysis of the impacts on the energy system of the temporal distribution of the electricity demand from electric vehicles. However, what is evident from the results is that there can be substantial changes in the energy system design depending on the temporal distribution of the load. Some of the largest changes observed include a decrease in installed solar PV capacity of over 19% when improving the temporal distribution of the electric transport load in 2030, and an increased installed capacity of almost 13% for lithium-ion batteries for 2050.

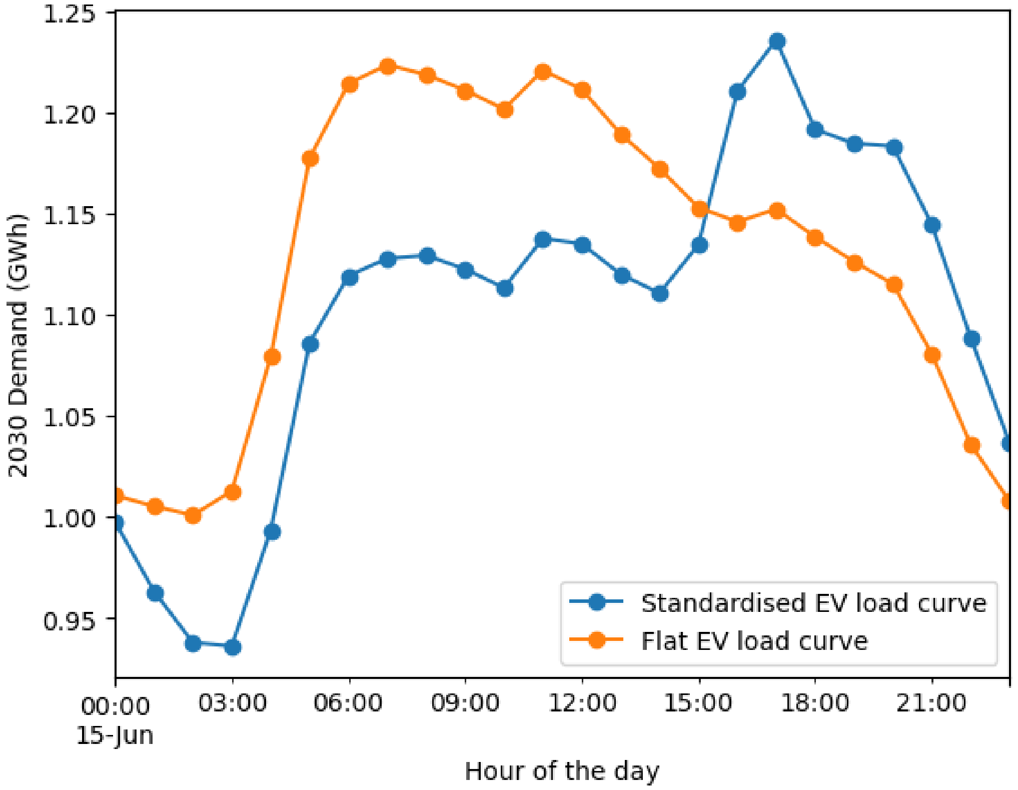


Figure 3-13: Difference in daily electricity demand for Oslo on the 15th of June 2030 when assuming the load profile from electric transport is equally distributed between the entire day and when using a standardised EV load curve.

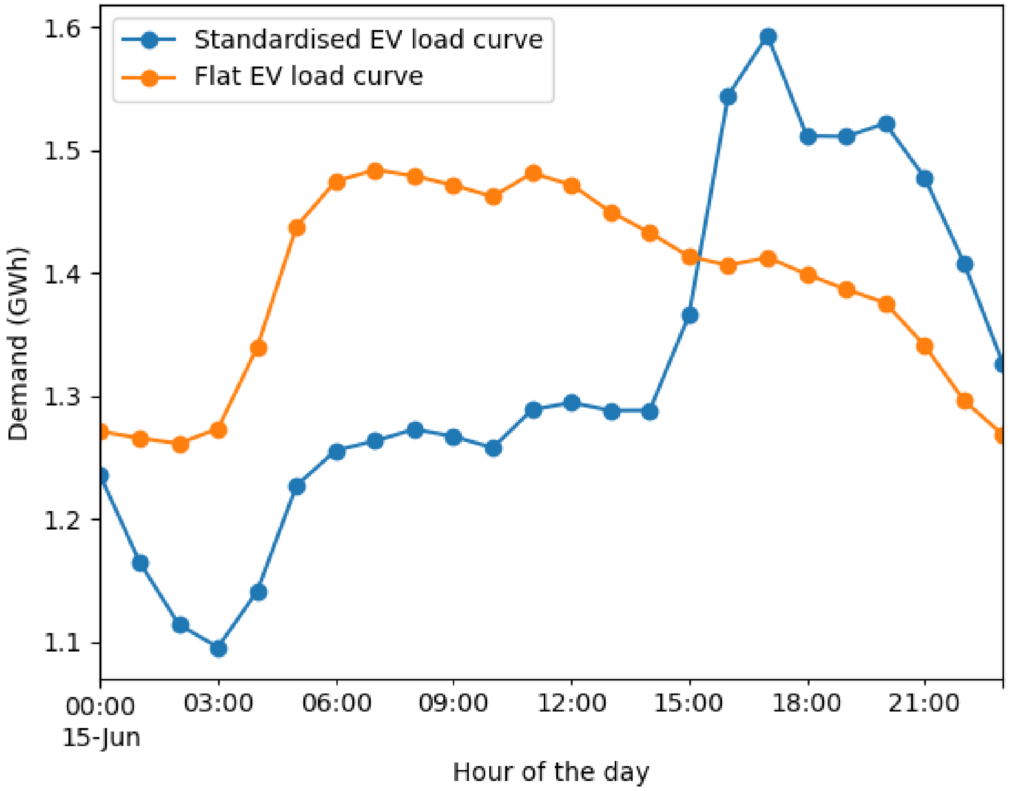


Figure 3-14: Difference in daily electricity demand for Oslo on the 15th of June 2050 when assuming the load profile from electric transport is equally distributed between the entire day and when using a standardised EV load curve.

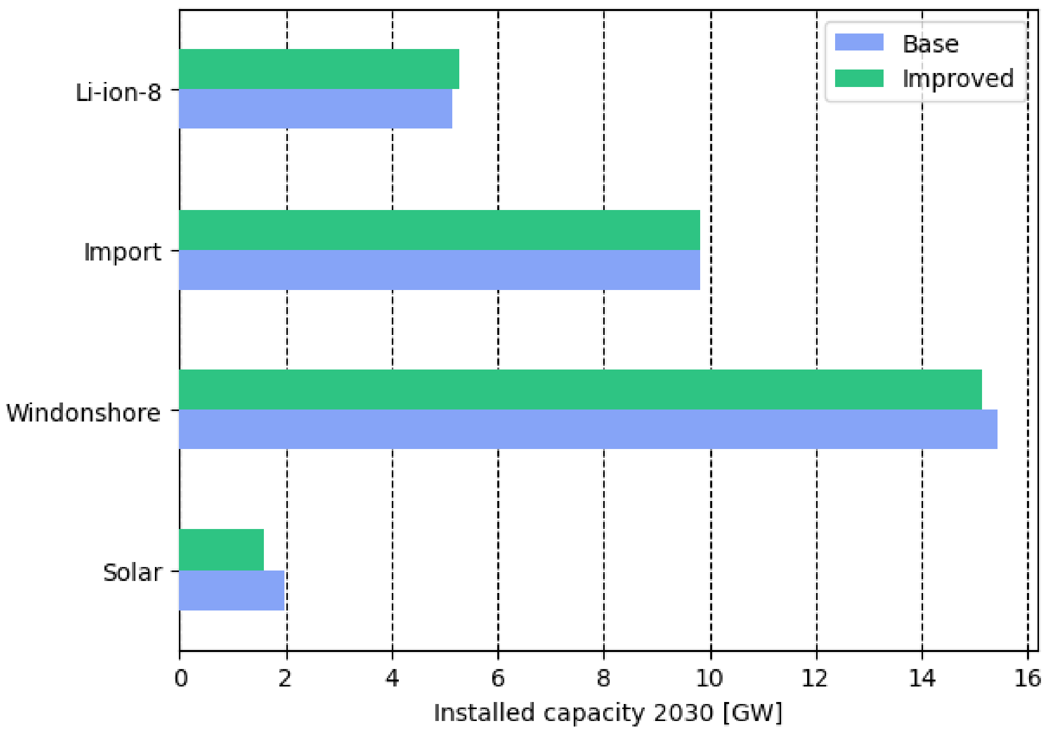


Figure 3-15: Installed capacities in the 2030 power system design based on 1995 weather data. Both with and without using the temporally improved demand from electric transportation.

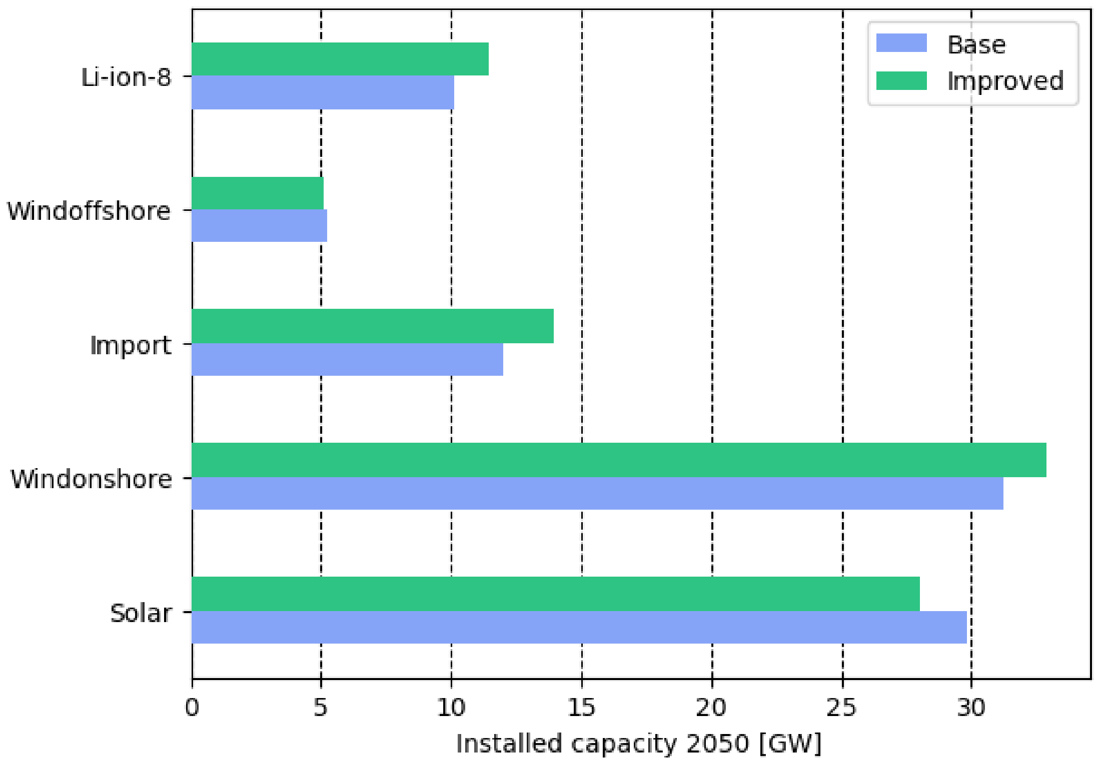


Figure 3-16: Installed capacities in the 2050 power system design based on 1995 weather data. Both with and without using the temporally improved demand from electric transportation.

3.7. Adaption of methods for iterative modelling of transport and energy systems

The main objective of this task was to investigate the properties of the energy system model GENeSYS-MOD and the transport sector specific model Energy map, and to evaluate how these models can be linked. This approach was mostly qualitative, focusing on insight into model structures and functions, harmonisation of input and output, and the possibility of interchanging information.

Technical challenges in iterative modelling

In order to properly link the models, we need to investigate how all of the pieces can be put together. If we intend to use the output from Model 1 as input to Model 2, and the output of Model 2 as input to Model 1, this will create a feedback loop as we expect the output to change due to the input. Creating a feedback loop requires a minimum compatibility level between the input and outputs of the models.

An important consideration is temporal and spatial disaggregation level. From a temporal disaggregation perspective, the output from the Energy map is one average weekday, which can be aggregated to a full year. Using established parameters to convert daily results to annual results, the output of the Energy Map is compatible with GENeSYS-MOD's aggregation level for inputs. This was partly tested in WP2 of the Nordic Energy Outlooks programme, cf. [2]. The temporal disaggregation in GENeSYS-MOD can be defined in two ways. In the first approach, the results are annually calculated with the possibility to be disaggregated into several user-defined time slices, which enables the user to produce results accounting for seasonality, weekday and weekends, and daily time bracket. The second approach in GENeSYS-MOD is based on a time reduction algorithm, which takes one hour every Nth hour and uses a nonlinear optimization method to scale and smooth the data to the original timeseries.This level of disaggregation is demanding to incorporate into the input of the Energy Map since the Energy Map does not account for seasonality in mobility demand. From a spatial disaggregation perspective, the Energy map and the associated transport models have varying disaggregation levels. The inputs and outputs of the models are mainly disaggregated to road-level/zonal level, while parameters for demand estimation are on a national level with the potential to be calibrated on the regional level (5 main regions). For GENeSYS-MOD, the disaggregation level is the 5 power price regions of Norway.

Moreover, convergence is desired when iterative approach is applied. In practice, it might be a time-consuming task considering the actual run time of the models. The transport models require several hours to run, at least at the national level. Thus, a series of iterations could take several days before convergence is reached.

Connection points between the models

An important consideration to make is the logical linking of models. The first step is to identify the connection points between the models where an output from one model can be used as an input to the other. As an example, which was partially explored in WP2, the energy use from the transport sector estimated by the Energy map can be used as input to GENeSYS-MOD. In WP2, this was only briefly investigated, for one specific sector and for one year. To take this a step further, we explored the most relevant connection points between the models, based on the technical description in Chapter 2. These are shown in Figure 3-17, and form the basis for the qualitative analysis.

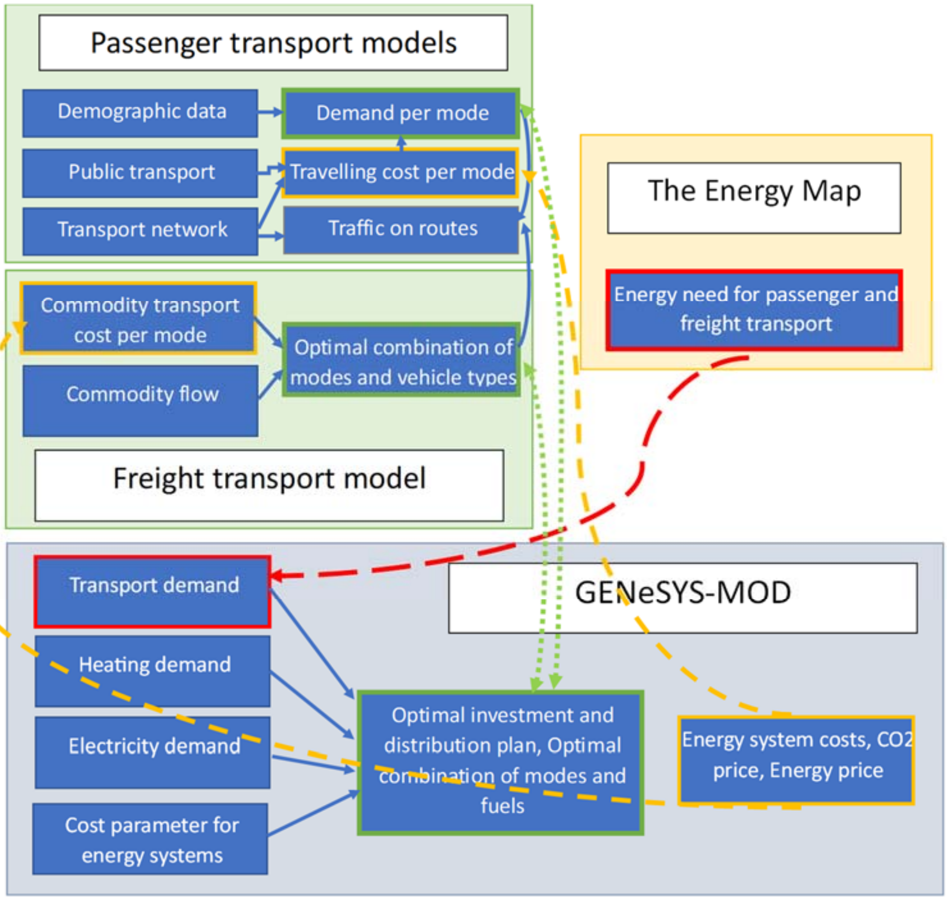


Figure 3-17: Identified connection points between GENeSYS-MOD and the Energy map.

As shown in Figure 3-17, another linking process would be to use the output from GENeSYS-MOD as an input to the Energy Map. When analysing the energy system using GENeSYS-MOD, it is possible to derive the CO_2 price and power prices under each scenario. One option is to use this information as an input for the generalised cost in the transport models.

As an example, in the REPowerEU scenario in WP2, cf. [2], the net export from the Nordic region to Europe increases by 30 TWh. This causes an increase in energy system costs in total, and especially in Denmark, but also in Norway and Sweden (In Norway 1752.2 million euro annually NPV). The extent to which the increase in energy system cost and increased export market affects power prices in different regions in the Nordic area should be investigated. It is worth mentioning that the energy consumption is assumed to stay unchanged under the REPowerEU scenario.

Contrary to what is assumed in the REPowerEU scenario, changes in total energy system costs, CO_2 price, and power price can be further used as an input to transport modelling and predicting transport demands in the coming years. Depending on the extent of cost change, it might trigger changes in overall demand for passenger transport, in the form of changes in frequency of the trips, length of trips, etc. The overall demand for freight transport remains unchanged as the freight demand is defined as price inelastic. Moreover, the modal shift for both passenger transport and freight transport might be affected by higher power prices, as the extent of change in costs might differ between different transport modes. For example, the cost of using electric cars might be more sensitive than other modes.

It should be noted that GENeSYS-MOD might give differential power prices for the 5 different regions. To incorporate differentiated prices into the national, regional and freight transport model, a rigid estimation method must be developed.

Both GENeSYS-MOD and the Energy Map include modal split as an endogenous function in the model. However, the approach for finding the optimal combination of modes is different in the models. GENeSYS-MOD has a system-optimal approach where the model finds a combination which is cost-effective for the total energy system. However, the transport models have a user-optimal approach, where the user chooses a mode which optimises their utility, which is not necessarily optimal for the total energy system. Although it might not be possible to use the results from one model to the other in this case, the difference in the modal split is useful to analyse how the two solutions differ and whether user travel behaviour must be diverted using effective measures and policies.

Scenarios and projections for electrification

The third research question is to investigate different scenarios and projections for electrification and development of transport and explore whether scenario parameters in National Transport Plan reference scenario is aligned with GENeSYS-MOD such as CO_2 price, the projected electrification rate and the projected modal split (See Table 3-5). The CO_2 price used in the GENeSYS-MOD scenarios vs the CO_2 price of the NTP scenarios can be seen in Figure 3-18, and the expected development of electric energy demand from road transport in Norway based on NTP projections and GENeSYS-MOD can be found in Table 3-6.

Table 3-5: Scenario parameters in NTP reference scenario 2050 vs GENeSYS-MOD scenario 2050

	NTP Reference 2050	GENeSYS-MOD- Gradual Development scenario 2050
CO_2 price	**2230 NOK/t (218€/t)** to be used in socio-economic analysis for price level 2023. The price is calculated based on a scenario where the world will reach to the United Nations' goals on being zero-emission within 2070. The temperature increase is calculated to be 1.65 degrees with the probability of 50% compared to pre-industrial age ([55], [56]).	**355 €/t:** CO_2 price in Gradual Development scenario, which is set for a 2° C compatible scenario, aiming to achieve a zero-emission energy system in 2050 [33].
Electrification rate	There is **no concrete goal on electrification rate** for transport in the National Transport Plan. Instead, there are several goals on achieving zero-emission transport within 2025 and 2030*. However, there are explicit references to the need for developing proper charging infrastructure, implying that electrification is considered a major factor in achieving zero-emission goals for transport. Moreover, it is mentioned that rail transport can be performed on electricity, and the technology development for electricity-driven trucks, heavy-duty vehicles and ships seems promising. This is not totally in line with the GENeSYS-MOD scenario in which the future freight land transport is dominated by H_2 and biogas. [57]	Electrification rate in transport is **estimated to be 70%** in Gradual Development scenario in 2050 ([33], figure 2-9)
Modal split	There is no concrete goal on modal split for passenger and freight transport, however, the projects estimated that using private cars will get cheaper due to the rapidly increasing share of electric cars and lower usage cost associated to them. However, this projection assumes that the power price does not develop differently than other price indexes. [57]	The projections on modal split in 2050 indicates that over 80% of passenger transport will be done by electric vehicles, while 10% by electric trains and the rest by air. The freight transport will be 75% on land with H_2 and Bio as the fuels. 15% by electric trains and the rest by Ship Bio ([22] figure 9 and 10)

*) By 2025, all new private cars and light-duty vehicles will be zero-emission vehicles and all new city buses will be zero-emission or will run on biogas. By 2030, all new heavy-duty vehicles, 50 percent of the new trucks and 75 percent of new long-distance buses will be zero-emission. Moreover, all freight transport in bigger city centres will be almost zero-emission.

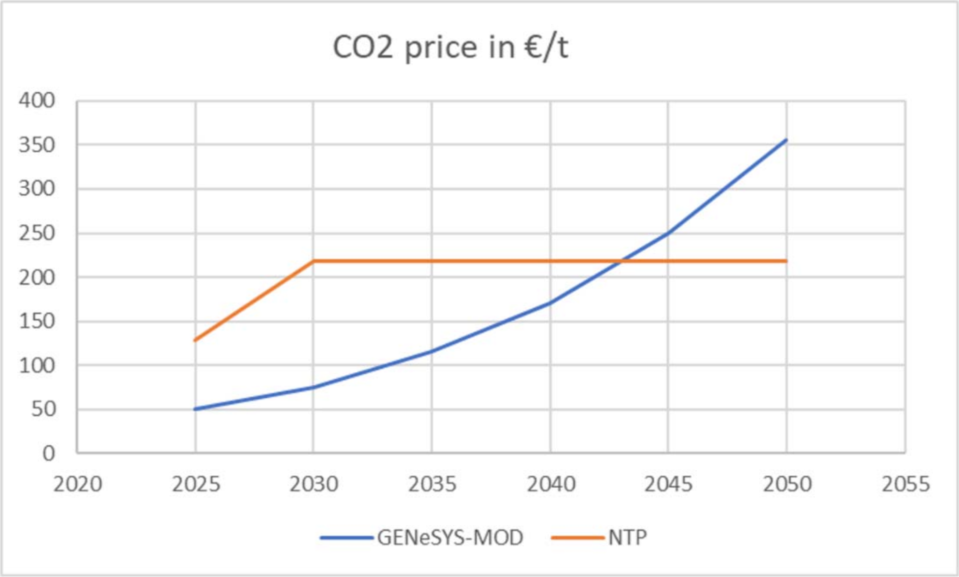


Figure 3-18: CO_2 price used in the GENeSYS-MOD scenarios vs NTP scenarios

Table 3-6: Expected development of electric energy demand from road transport*) in Norway based on NTP projections and GENeSYS-MOD scenario Gradual Development in 2050. All numbers in GWh/year.

Region*	GENeSYS-MOD (2050)	NTP (2050)**
NO1	4412	3092
NO2	2541	1712
NO3	1454	820
NO4	935	424
NO5	1165	720
Sum	10507	6 768

*) Power-price regions are defined as: NO1 as counties Viken, Oslo, Innlandet, NO2 as Vestfold og Telemark, Agder, Rogaland, NO3 as Trøndelag, Møre og Romsdal, NO4 as Nordland and Troms og Finnmark and NO5 as Vestland.

**) Source: Energy map. Excl. public transport.

3.8. Discussion of results between models

Incorporating risk of critical raw materials supply in GENeSYS-MOD and the Energy Map

The risk of lacking critical raw materials might affect the production of electric vehicles, which consequently might affect availability and the price of these vehicles. These two parameters are not properly modelled, neither in the passenger transport model, nor in the freight transport model. The car ownership model in the passenger transport model is mainly dependent on the socio-demographic characteristics of the residents, rather than the relative vehicles market price in relation to the income level of the population. However, a smaller number of electric vehicles might affect the modal split, leading to less car use than anticipated as opposed to public transport, cycling ang walking, as the cost of driving an electric car is lower than the cost of driving a fossil-fuel car in the model.

Critical material supply for electric cars could be added as a new constraint in GENeSYS-MOD. If the new constraint is binding, it will lead to higher energy system costs and a non-zero price for the use of material on top of what is already included in technology costs. A new binding constraint will affect many model results, also including dual variables on other constraints. Possibly the power price will decline due to less use of electricity in transport, while the CO_2 price will increase since other mitigation measures must be used instead.

Fuel options in aviation and harmonising assumptions between IFE-TIMES-Norway and ON-TIMES scenarios

The explorative analysis of potential fuel options in the aviation sector introduced new input assumptions into the IFE-TIMES-Norway model, mainly including technology details and investments costs for DAC and synthetic fuel production plants. These assumptions mimic the inputs used in the ON-TIMES model, which have as original source inputs from the Danish Energy Agency's technology data. However, some differences in the projected uptake of fuels replacing conventional fossil fuel consumption in aviation are seen when comparing the results from both models.

Differences in the modelling results can be explained by the fact that some of the technology inputs, namely for DAC used in the IFE-TIMES-Norway model, present more up-to-date estimates in terms of efficiencies, and expected investment costs despite coming from the same underlying source. In addition, more recent planned projects specific to Norway are only included in the IFE-TIMES-Norway model, thereby accounting for new supply options of synthetic fuels to be produced by these upcoming plants. Furthermore, the updates in the IFE-TIMES-Norway model also incorporated additional constraints on the allowed fossil fuel production which mimic long-term EU policy targets, as proposed by the Fit for 55 package and ReFuelEU Aviation initiative. Ultimately, these factors lead to somewhat different overall trends in the uptake of sustainable aviation fuels across the scenarios presented by the two models.

The representation of the aviation sector can also be an area of additional development since both models have a different coverage of the demands from the sector. In IFE-TIMES-Norway, only domestic aviation is represented. Meanwhile, the ON-TIMES model has a wider coverage including both domestic and international aviation (the latter represented by the shared fuel in the Nordic countries), which in total represent about double the energy consumption compared to the domestic aviation presented in IFE-TIMES-Norway.

Overall, the alignment of these aspects across both models could facilitate the comparison of results and provide a wider perspective of the role of sustainable aviation fuels in potential pathways in which the aviation sector can develop both nationally and in a wider Nordic perspective.

Further improvements of the representation of electricity demand from the transport sector in highRES

The work on improving the spatial and temporal electricity demand from the transport sector focused on road transport and battery electric vehicles in particular. However, the transport sector is more than just road transport and also includes aviation, for instance. Section 3.3 on emerging fuels and technology options in the aviation sector, the decarbonisation of the domestic aviation sector in Norway is covered. The results show that options including battery electric airplanes, e-fuels and hydrogen are used in the decarbonisation of the sector. Similarly to when road transport is electrified, these technologies also cause an coupling of the transport sector and the electricity system. Battery electric airplanes connect directly to the electric grid when charging, while e-fuels and (green) hydrogen require electricity to be produced. The results showing the future demand for these options reveal a possible approach for improving the electricity demand input to models such as highRES: including the demand from the decarbonisation of the aviation sector.

3.9. Workshops

During the project, three workshops where organised to discuss important topics for the ongoing research. The themes for the workshops are:

- Visioning as a tool in scenario building (DEA)
- Critical raw materials for the energy transition - Methodologies for Energy Systems Modelling (UiO)
- Scenarios for decarbonising the Nordic transport sector (IVL)

This section describes the purpose of the workshop, the agenda, and to report some main parts of the discussions.

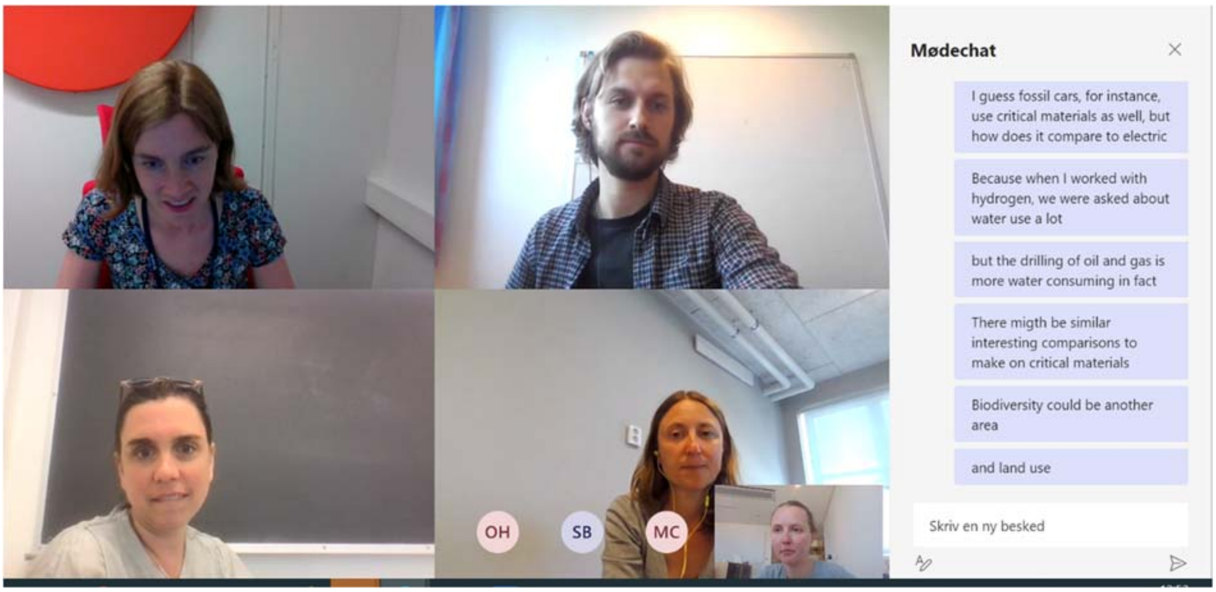
Visioning as a tool in scenario building

Purpose of workshop with NEO

The purpose of having a workshop with the NEO group was to have a discussion on how we usually go about assumptions and inputs for our scenario building, and to get inputs on the suggested alternative approach using visioning with external contributors.

Workshop agenda

During the workshop with the NEO group, the Danish Energy Agency presented our latest theoretical work and first experience with facilitating visioning workshops with external experts. Recently, the Danish Energy Agency facilitated a visioning workshop on future mobility in Denmark 2050 for a group of ten mobility experts from various fields and backgrounds. The presentation led to a very fruitful discussion on the approach as an additional tool for scenario building. At the end of the workshop, it was decided that DEA will host a visioning workshop at the final seminar for the WP4 with the NEO group. A snapshot of the online workshop is shown in Figure 3-19.



I guess fossil cars, for instance, use critical materials as well, but how does it compare to electric

Because when I worked with hydrogen, we were asked about water use a lot

but the drilling of oil and gas is more water consuming in fact

There migth be similar interesting comparisons to make on critical materials

Biodiversity could be another area

and land use

Figure 3-19: Snap-shot from online workshop

Discussion in the NEO group on choice of participants for the visioning process

The workshop included a discussion on the choice of external participants for visioning workshops. It is a crucial part of the visioning, since the inputs for the scenario building depend highly on the participants' academic backgrounds, personal views, level of perspective and so on. Therefore, the scenario inputs from a visioning workshop are not to be compared with an experiment in disciplines such as Physics or Chemistry, where results are replicable. Rather, the results will differ from day to day even with the same group of participants. The purpose then, is not to arrive at a universal 'truth', but to capture trends, signals and opportunities for major shifts in technologies, societal values and the like, that cannot be captured with the present-day approach because they are not yet visible in the historic data or in current statistics but occur only as vague ideas or niche products. The participants should preferably be knowledgeable on the topic, present ideas compatible with the laws of physics, have a good overview on the problems and opportunities ahead, and have a long-term perspective on their field. Nevertheless, there is a risk that participants have blind spots, which was perhaps the case with the specific group of participants for the trial workshop on mobility facilitated by the Danish Energy Agency, since the selected participants as a whole had more focus on mobility in larger cities than on mobility on the countryside. As a follow-up, one or more additional visioning events with other groups of participants could broaden the perspectives. The discussion in the NEO group also covered the willingness of the participants to set aside the time for the visioning, which based on the experience from DEA has not been an issue to this point. On the contrary, the participants expressed their excitement to be given the chance to discuss these topics. The DEA report that they wouldn't be surprised if the participants even were to continue with these ideas outside of the workshop.

Discussion in the NEO group on incorporating visioning inputs into energy models

There was a lengthier discussion on how to incorporate inputs from vision workshops into currently used energy models. The difference in result format makes this a particular challenge, since the input from visioning workshops are most often qualitative, while the inputs to the models are quantitative with high levels of detail. In other words, how can the results from the visioning workshops be translated into qualitative inputs for the models. One way to solve this is to force or encourage the participants to quantify their ideas – e.g. if they say "In 2050 the car park is smaller", we would ask for more details "what would be the size of the car park in 2050 relative to today? When would the change start to happen?". Next, we would have to check, whether their ideas actually work as inputs to the models and perhaps gather the participants for a follow-up to ask them if this was what they intended. Another approach is to use the visioning inputs more qualitatively as suggestions for adding new model options, new technical solutions etc. Finally, we can get inspiration on how to present our model scenarios and model results qualitatively by visualising the scenarios, use storytelling and so forth.

Critical raw materials for the energy transition - Methodologies for Energy Systems Modelling

The aim of the workshop is to discuss the importance of considering the impact the increasing use of raw materials will have on future energy systems. Access to raw materials is essential both for the technologies used to decarbonise the transport sector, and for the renewable energy technologies needed to supply the transport sector with clean energy.

The workshop aims discuss the following two topics:

1. The methodology to represent social and environmental factors and supply side constraints of materials in energy system models.
2. How the European Commission's work on Critical and Strategic Raw materials can be taken into account in the NECPs.

We started the discussion around how supply risk may change in the future as the proposed methodology by UiO assumes that the risk will stay the same in 2050 as in latest report of the European Commission. Suggestions to build up on this were to 1. Perform an assessment on which risks will improve and which ones get worse and 2. Look at past developments based on the EU report (which is being released every 3 years). We also discussed how to balance the non-economic part in the objective function, which will be challenging.

It would also be interesting to include regional numbers on risks instead of worldwide averages (e.g. mining has different risks and benefits depending on the country). On that note, there could be gains of mining and producing materials within the Nordics which would be interesting to explore.

We discussed that recycling of material and representing a circular economy will be more relevant in the future. However, the current state of material in circulation is low and there is a lock-in time of materials before one can recycle them. The increase in mining will be very important for the next few decades and 2050 could be a time when recycling starts to play a role.

Critical raw materials are not being mentioned in the Norwegian NDC (nationally determined contribution under the Paris Agreement) and we suspect that it is the same for other countries. In general, the NDCs do not go into this level of detail. In other countries such as Sweden, critical materials are often discussed in connection with batteries but not in connection with the entire energy system. However, a lot of materials are in competition within the energy system (e.g. magnets in batteries and wind turbines).

Apart from supply risks, the work shall also be extended to consider social and environmental risks (and benefits) of mining activities. It is also important to compare scenarios to status quo fossil scenarios as they also consume materials and have negative social and environmental impacts.

Scenarios for decarbonising the Nordic transport sector

Purpose and agenda of the workshop

The aim of the workshop on scenarios for decarbonising the Nordic transport sector with the NEO WP4 team was to increase knowledge of each other's models and scenarios and to discuss the possibility of harmonising the scenarios used in the different analyses by different partners.

All partners participated in the workshop. During the workshop, all partners presented their assessments and the scenarios they were planning on including in the work. Then, there was an open discussion on the possibility of harmonising the scenarios across the partners.

Summary of overall scenario approaches and discussion on common scenario narrative in NEO WP4

As the assessments made by different partners are quite different, with distinctly different topics and approaches, the WP4 team agreed that it is neither possible nor adds value to have one or several common scenarios in WP4. However, IFE and IVL agreed to have a separate bilateral meeting to discuss the possibilities of having a common scenario narrative and exchange of knowledge and assumptions between the assessments made by the ON-TIMES/GAINS model and the IFE-TIMES-Norway model, which are more similar. The outcome of that discussion was that the scenarios planned to be used in the ON-TIMES and IFE-TIMES-Norway model assessments from an overall perspective are similar and represent a common scenario narrative for the assessments made with these models in WP4. It was also decided, as part of the project, to harmonise the assumptions made for the aviation sector in the IFE-TIMES-Norway model with the ON-TIMES model to the extent relevant and to include a comparison of the results in terms of fuel options in aviation between these two models (presented in Section 3.8).

The assessments by SINTEF have a Norwegian national perspective and are based on scenarios from the National transport plan (reference scenario and scenarios representing transport system changes). SINTEF will assess how the scenario parameters align with the GENeSYS-MOD. The assessments by UiO also have a Norwegian national perspective and the scenarios will focus on reaching net zero GHG emissions by 2050. DEA focus on improving the input data for their scenario and energy system models. The assessments by IFE have a Norwegian national perspective as well and are based on scenarios including different levels of technological change and socio-institutional change. All in all, there are four different scenarios in their scenario framework named incremental, technological, social, and radical. As a result of the discussion on a common scenario narrative, the Radical scenario from FME NTRANS was selected (see Section 4.3) to illustrate a transition pathway where there is a high degree of both societal and technological change in line with the assumptions presented in the Carbon Neutral Nordic (CNN) scenarios from the ON-TIMES model, developed for the Nordic Clean Energy Scenarios project. The assessment by IVL have a Nordic perspective and will focus on results for Sweden, Norway, and Denmark, to align with the other partners work in WP4. The scenarios used by IVL are based on the scenarios developed for the Nordic Clean Energy Scenarios project. IVL will include both the CNN scenario as well as other scenario variants in their assessment to provide a broad picture of potential effects (see Section 3.2).

5. Inputs to the update of National Energy and Climate Plans (NECPs)

5.1. Sweden

The following text focuses on commenting the draft update of the Swedish NECP (prepared by the Swedish Energy Agency and sent to the Swedish government on 4 April 2023 [58]), from the perspective of air pollution.

In the draft update of the Swedish NECP (Swedish Energy Agency, 2023), it is acknowledged that air pollution and climate change are closely interconnected in many ways. The factors and activities causing climate impact, also contribute to air pollution. Additionally, it is emphasised that a changing climate affects the exposure to air pollutants. Hence, there are strong reasons to coordinate policies to benefit both aspects.

The transportation sector is, in the draft update of the Swedish NECP, identified as one of two strategically important areas regarding potential synergies and conflicts between air quality and climate goals. It is generally acknowledged that the progress within the transportation sector will be crucial for achieving Sweden's nitrogen oxide (NO_x) emission targets by 2030, as well as addressing other air pollutants. In the government's decision on the national air quality program, measures to achieve the climate goal for transportation by 2030 are highlighted as part of the actions within the air quality programme aimed at reducing NO_x emissions.

In particular, the proportion of the vehicle fleet powered by internal combustion engines until 2030 is emphasised as crucial for the trajectory of NO_x emissions. EU regulations on CO_2 for vehicles and equivalent requirements for heavy-duty vehicles can thus have a positive impact on NO_x emissions by 2025 and 2030. Increased electrification, energy efficiency, and a transport-efficient society are identified as particularly positive measures, which is also confirmed and quantitively illustrated in the relevant assessments in this report.

The draft update of the Swedish NECP further points out that increased use of biofuels can play a significant role in the decarbonisation of the transportation sector, but may have limited or no effect on air quality. Biodiesel has approximately the same NO_x emissions as fossil diesel, while biogas has slightly lower emissions. Therefore, it is emphasised that a more transport-efficient society and increased electrification are the key measures to achieve air quality goals. This is also confirmed and highlighted in the assessment in this report.

Collaboration with other Nordic countries is generally identified as important for the green transition in Sweden by the Swedish NECP. However, cooperation on climate and electricity is specifically mentioned, and nothing concrete is mentioned about the need for collaboration to reduce air emissions from the transportation sector. We think it is important to have strong Nordic collaboration in this area.

5.2. Norway

Norway does not have a national energy and climate plan (NECP) as EU countries have. In 2021, however, the government did publish their plan for climate action from 2021 to 2030 [59]. The plan details how Norway will achieve the cuts in greenhouse gas emissions as committed to under the Paris

Agreement (at least 50% and up to 55% reduction of greenhouse gas emissions in 2030 compared to the 1990 level [13]).

For the transport sector, Norway's Climate Action Plan states that the goal is to reduce emissions by 50% by 2030. Passenger cars are the highest emitting part of the transport sector [59, p. 66]. The transition to electric vehicles is presented as a crucial part of the decarbonisation, promoting batteries as an essential technology in the transition.

Supply risk of critical raw materials

The aim of this section is to comment on how the Climate Action Plan takes into account raw materials critical for the net-zero energy transition. Concerns are arising on the material demand of the green transition. These concerns include everything from resource availability, social and environmental impacts of the mining, to the concentration of raw material resources, processing and supply. The Climate Action Plan has been reviewed to identify how critical raw materials are addressed. Specifically for battery technologies, there is a short discussion [59, p. 84]. It recognises battery technology as a key technology for the transition, and mentions the concerns around increasing material demand and the issues around the mining of raw materials. Incentives in the EU to establish a battery industry and ensure material recycling are brought up together with the potential in Norway for establishing an industry around the development and production of battery technology and recycling of materials from batteries.

The European Commission identified a list of 34 raw materials considered to be critical to the European economy [53]. Nine of the materials on the critical raw materials list are used for lithium-ion batteries, which are essential for electric vehicles. The critical materials for lithium-ion batteries are lithium, natural graphite, cobalt, manganese, nickel, copper, phosphorus, aluminium, and fluorspar.

We believe that the Norwegian government's Climate Action Plan could benefit from taking into account the critical aspect of the materials needed for technologies suggested as important measures to reduce greenhouse gas emissions. Doing so could help address the feasibility of the climate plan and identify areas of focus to ensure its success. While this section focuses on commenting the use of lithium-ion batteries for electric vehicles, we suggest that a similar approach is also taken for other technologies, such as fuel cells, photovoltaics, wind turbines, etc. While the plan did mention concern around raw materials for battery technology, this is not the case for other technologies considered in the plan, and the plan did not provide any suggestions on how Norway could proceed to mitigate such issues. Thus, we suggest to adapt the European Commission's assessment of critical raw materials to develop a plan to ensure a sustainable and secure sourcing of raw materials.

The European Commission's Critical Raw Materials list is likely relevant to all Nordic countries – especially to Denmark, Sweden and Finland as they are members of the EU and thus also included in the assessment.

Road transport

For the road transport sector, the governmental goals for 2030 are presented in the National Transport plan. It states that by 2025, all new cars and light vans should be zero emission. Similarly, the target for urban buses by 2025 is that all new vehicles will be either zero emission or run on biogas. Concerning the heavier vehicles, the goal for 2030 is that all new heavy vans, 75 % of new long-distance buses and 50 % of new HDVs will be zero emission.

Considering the current situation of zero emission vehicles in Norway, the situation is quite promising regarding the stated goals. This is especially the case for cars, which are overachieving the estimated trajectory needed for the 2025 goals. In the Climate Plan, several areas are targeted for making sure all goals will be met by 2025 and 2030. An essential part of this to continue the efficient use of incentives and policies. On the private side, ENOVA (a state enterprise owned by the Ministry of Climate and Environment) is an important instrument for supporting early adoption of green technology choices in the transport sector. This is especially relevant for heavy vans, HDVs and long-distance buses. On the public side, the power of public procurement is highlighted as an instrument for policy push. Norwegian governmental bodies are one of the largest buyers of transport services, especially in urban areas, and can increase the evaluation impact of zero emission vehicle use in tender design, both for urban logistics and public transport.

Another important area in the Climate plan is the availability of charging infrastructure. Although the existing infrastructure for cars and vans is considered to be very good, this is not intended to be used for heavier vehicles. Therefore, this needs to be extended at a large scale. The main guideline for infrastructure expansion is to let this be run by the private market, with some governmental support through ENOVA where needed. This is mainly directed at publicly available fast charging stations. However, it is also important to ensure a sufficient level of charging infrastructure in buildings, both private and corporate. This will be handled through changes in building regulations to facilitate and encourage the installation of chargers in new buildings.

Except for the charging infrastructure topic, the Climate plan is in general technology neutral with regards to vehicles. This stems from the focus on zero emission, regardless of technology. Therefore, the role of hydrogen in the road transport sector is not taken into consideration as it is for other modes. In addition, the need for a Nordic cooperation is explicitly mentioned in the context of hydrogen value chains. This should also be extended to other zero emission technologies to ensure a seamless and consistent supply of energy to border crossing transport.

Aviation and Maritime Sectors

In Norway's Climate Action Plan [60], the maritime and aviation sectors are addressed as key sectors for further use of low-emission technologies and climate mitigation efforts. In Norway's Climate Action Plan [60], the maritime and aviation sectors are addressed as key sectors for further use of low-emission technologies and climate mitigation efforts. Existing measures already address – to different extents – the decarbonisation of these sectors. For example, a biofuel quota obligation is in place for domestic aviation, setting a 0.5% jet biofuel obligation on the sales of total jet fuel. Furthermore, companies in this sector can be eligible for grants to develop and phase in low-carbon technologies. Meanwhile, for the maritime sector, a number of measures are already in place for the different vessel segments as further outlined in the Government's action plan for green shipping [61]. The plan proposes additional measures for these two sectors.

In the Climate Action plan, reducing maritime transport emissions is highlighted as one of the priorities for the Norwegian Government. Consequently, the current plan addresses in detail potential abatement measures for the different vessel segments in the maritime sector. The plan also highlights the promotion of technological development in maritime transport as a value creation opportunity for Norway, given its current international leadership in the sector. It explicitly addresses new energy carriers as potential alternatives for the decarbonisation of the sector – which, as highlighted in this report - could provide valuable fuel substitutions and contribute to the CO_2 abatement of the sector. Finally, international collaboration is addressed as a key element given the global nature of the industry and ongoing international efforts such as those set by the International Maritime

Organisation, the proposals set within the context of the European Green Deal, and Nordic cooperation supporting the transition to green shipping.

For aviation, the current plan proposes raising the carbon tax on ETS emissions for domestic aviation. It also suggests additional testing and development of new aviation technologies and infrastructure, as well as proposing additional collaboration with Nordic countries and with aviation authorities in Europe to foster the deployment of low-emission aircrafts and related technology. However, no explicit suggestions are made on the type of technologies that could be considered or specific actions regarding cooperation with other Nordic countries or regionally with Europe besides adhering to the current application of the EU emission trading system and with targets set by international aviation organisations.

Existing proposals at the European level address in more detail the potential introduction of low-emission initiatives in the aviation sector. Namely, the introduction of sustainable aviation fuels and the proposal to ensure a levelled playing field to ensure their uptake [62], [63]. This proposal could be a point to further develop in Norway's Climate Action Plans, by more explicitly including additional consideration of sustainable aviation fuel pathways and contextualising the development of the Norwegian aviation sector's fuel supply in tandem with other Nordic countries as EU member states. Additional research and development of synthetic jet fuels could provide new low-emission pathways to substitute fossil fuel consumption in the sector, as highlighted in this report. However, synthetic fuels might remain a more expensive alternative to conventional fossil-based jet fuel [64]. Thus, new regulations and measures will also need to be further studied to assess how sustainable aviation fuels, including synthetic fuels, can be deployed to meet Norway's climate targets in a levelled playing field.

6. Future research

6.1. Decarbonising the aviation sector

Rationale:

Sustainable aviation fuels and new aircraft technologies might play a more prominent role to decarbonise the aviation sector but are captured to a limited extend in current plans and models. Identifying carbon capture options available also remains a key challenge.

Expected outcome:

More detail on sustainable aviation fuels, new aircraft technologies and carbon capture options could aid in decision-support to expand current plants and showcase new potential pathways in the sector.

Scope:

Mapping potential sources of biogenic CCUS in the Nordics, that could be used as feedstock for synthetic fuel production. Identification of new aircraft technologies, and their related costs and value chains that could be included in energy system modelling analysis.

6.2. Environmental impacts of decarbonising the maritime sector

Rationale:

The decarbonisation of the maritime sector in the Nordic region need to be enhanced. Currently there are several policy initiatives under development in the EU. There is a need to analyse the potential environmental effects (GHGs and air pollutants) for Nordic shipping of the proposed shipping policies. It is also important to assess the possibilities for different alternative marine fuels (including ammonia) and propulsion concepts linked to the implementation of these policies, partly to better represent the future role of different option in energy system modelling analyses.

Expected outcome:

Increased understanding of the environmental effect of soon implemented policy initiatives for the shipping sector and the potential future role of different marine fuels in the Nordic region.

Scope:

Analyses of the impact of the relevant policies on the emissions of GHGs from shipping as well as other environmental impacts. Analyses of the conditions and possibilities for different alternative marine fuels (and propulsion concepts including marine fuels that are not yet introduced in large-scale e.g., ammonia and for which the performance in terms of cost and emissions are still relatively unknown) within the framework of the relevant policies. Assess how the policies should be represented in the Nordic energy and transport system models.

6.3. Raw material supply risk

Rationale:

A methodology on considering critical raw materials in energy system modelling has been proposed in this report. That methodology is just the first step, and more research is needed to implement and apply it.

Expected outcome:

By taking the risks associated with the supply of critical raw materials for the energy transition into account it is expected that energy system models can provide optimisations showing greater resilience against these risks.

Scope:

Implement the proposed methodology in an energy system model (highRES in particular) and through this assess the impact which critical raw materials can have on future energy systems.

6.4. Update and harmonisation of scenario assumptions

Rationale:

As technology options (such as hydrogen-based fuels) develop the performance in terms of cost, emissions, and efficiency as well as need for critical raw materials may change substantially. Thus, energy system models need to be continuously updated in terms of data and assumptions linked to technology options to better capture the prerequisites for different options.

Expected outcome:

More up-to-date assessments of the potential future role of different transport modes and transport fuels in aviation, shipping, and heavy-duty road transport.

Scope:

Update data and assumptions for key technology options in energy system models and compare and harmonise the data between different energy system models in the Nordic countries to improve them further.

6.5. More detailed analyses of the environmental effects of Nordic transport transition pathways

Rationale:

The environmental effect of different decarbonisation strategies need to be studied further. Decarbonisation of the transport sector to some extent move the emissions from the transport sector to other sectors (such as in the case of electrification, where the electricity as well as electric cars are produced in other sectors than the transport sector) and potentially also to other countries.

Expected outcome:

Increased understanding of the sustainability of different decarbonisation strategies and to what extent emission impacts are covered by current policies.

Scope:

To assess the impact of different decarbonisation strategies on emissions of air pollution from a broader perspective, transport-related emissions from other energy sectors (e.g., from electricity production for electric vehicles) should also be included. In addition, more detailed assessment of the environmental effect of different decarbonisation strategies in the Nordic countries are needed.

7. Concluding remarks

7.1. Summary

Emerging fuels and technology options in the aviation sector

The introduction of additional detail in the representation of the domestic aviation sector in IFE-TIMES-Norway brings about noteworthy changes in the resulting fuel mix, which include varying levels of sustainable aviation fuels. In this regard, two key aspects were explored: 1) the role of hydrogen as an alternative to conventional aviation fuels when applying conservative assumptions on the rollout of hydrogen-based aircrafts, and 2) the potential role of electrofuels as a direct fuel replacement in internal combustion engines for domestic aviation aircrafts.

The conservative assumptions for the role of hydrogen led to pathway with more fossil fuel consumption in the early stages, and a more progressive consumption of biofuels towards 2050. Building upon this development, the introduction of synthetic fuels brings about a lower fossil fuel consumption, and consequently lower CO_2 emissions in the aviation sector. In tandem with this, biofuels are also expected to play a more prominent role, thereby further contributing to the decarbonisation of the sector.

Environmental effects of Nordic transport transition pathways towards climate neutrality

An example of how the impact of air pollution linked to various scenarios from Nordic energy systems modelling can be assessed is provided. The study confirms that the environmental effects of various strategies for decarbonisation of Nordic transport modes can be assessed by soft-linking the ON-TIMES model and the GAINS model via modelling data transfer tool, developed, and adapted in this project while focusing on the transport sector. Scenarios for decarbonising the Nordic transport sector including varying levels of different key measures and options (such as electrification, biofuels, hydrogen, and transport demand) were developed based on earlier assessment with the ON-TIMES model and tested using the data transfer tool. The impact on fuel and transport technology choices, and on the most common emissions of air pollution e.g., NO_x emissions and PM emissions were explored for road transport, shipping, and aviation.

The study clearly indicates that it is interesting to also address emissions of air pollution linked to Nordic energy system model assessments to obtain a broader picture of the sustainability of various scenarios and strategies. The assessment confirms that electrification of transport, as expected, will reduce the emissions of NO_x (and this will be the case for all transport modes as well as in all assessed Nordic countries). It also shows that reductions in energy transport demand will, because of lower fuel use, lead to lower emissions of air pollution and that a shift to biofuels will not influence air pollution in the assessed Nordic countries to a major extent. Increased use of hydrogen will also lead to reductions in terms of emissions of NO_x and particles.

Adaption of methods for iterative modelling of transport and energy systems

GeneSys-Mod was linked to transport models to explore to which extent to which the introduction of a higher degree of details from domain specific models will improve the results from an energy system model. Three main topics were investigated. Firstly, the technical challenges in iterative modelling were addressed. We found several differences in spatial and temporal resolution. Although this can to some degree be negated through technical adjustments, the missing seasonality in transport models is an important barrier for harvesting the full potential of model linking. In addition, the computational run time is identified as a potential significant practical issue in an iterative approach. Then, the main connection points between the models were identified. These were mainly focused on the circularity of input and output and revolved around cost data and modal split. This is based on the fundamental principles of how changes in energy costs will affect the transport demand. A potential barrier for the cost connection points is the difference in how modal split is modelled. While GENeSYS-MOD has a system-optimal approach, the transport models have a user-optimal approach. Finally, the scenarios and projections related to electrification of the transport sector was investigated. Some of the most prevalent differences regarding scenario parameters were described, and the differences in projected development of demand for electric energy from road transport were presented at the national price region level. Some of the differences could be explained by the scope of the models.

Critical raw materials and temporal distribution of electricity demand in energy system modelling

The multi-objective optimisation methodology to implement supply risk considerations presented provides a starting point to the work of considering and applying this into energy system models. Going forward from this the methodology will be used to create a version of highRES which optimises the electricity system not only to minimise the total system cost, but which also reduce the risk associated with the supply of raw materials. Furthermore, the importance of the temporal distribution of electricity demand from the transport sector was analysed to see how the installed capacities of generation technologies and energy storage together with the total cost of the system changed as a result of improving this. The results from this part of the work are summarised in the main findings section.

Qualitative methods provide alternative insights into transport futures

Possible 'transport futures' can be studied in different ways. Here, we have compared a model study aiming at a 'probable future' with two qualitative studies aiming at 'preferred futures'. The model study was 'Climate Status and Outlook' published by the Danish Energy Agency in 2022, which is a Frozen Policy study of energy and carbon emissions till 2035 in Denmark, including transport. The qualitative studies chosen were a) a workshop facilitated by Danish Energy Agency in 2022 on visions for future transport, with the participation of ten Danish mobility experts from different fields, and b) the 'Danish Citizens' Assembly on climate', consisting of 99 representative citizens, which has presented a list of recommendations for Danish climate politics in 2021, including recommendations on transport.

7.2. Main findings

The main findings from the assessment of environmental effects of Nordic transport transition pathways towards climate neutrality include:

- The environmental effects of various strategies for decarbonisation of Nordic transport modes can be assessed by soft-linking the ON-TIMES model and the GAINS model via a modelling data transfer tool.
- Electrification of transport will reduce the emissions of NO_x (and this will be the case for all transport modes as well as in all assessed Nordic countries).
- A shift to biofuels (from fossil fuels) will not influence air pollution in the Nordic region to a major extent.

- Reduced energy transport demand will in total lead to lower emissions of air pollution due to that less fuels emitting air pollution are used in such scenarios.
- There is a considerable potential for emission reductions both in terms of CO_2, NO_x and particles linked to the potential increased use of hydrogen for shipping (as well as other transport modes).
- To obtain a broader perspective also transport-related emissions from other energy sectors (e.g., from electricity production to be used in electric vehicles) should be included in the assessment. This imply that the modelling data transfer tool developed for the assessment in this study needs to be further elaborated.
- More detailed and comprehensive assessments of the impact of air pollution of different decarbonisation strategies than were possible within the scope of this project is called for as it is important to be able to assess carbon abatement and abatement of other air pollution at the same time.

Main findings from the explorative analysis of emerging fuels and technology options in the aviation sector:

- Biofuels are expected to play a larger role covering aviation demands if hydrogen aircrafts have a limited and gradual rollout from 2035 onwards
- A partial shift to synthetic aviation fuels can be supplied with the realization of planned projects, however investments in new additional capacity are not cost effective in the intermediate stages of the transition towards 2050
- Fuel replacements with biofuels and hydrogen remain more cost-effective options and are expected to cover larger shares of the domestic aviation fuel consumption.
- Including synthetic aviation fuels can help in the abatement of the remaining carbon emissions from the sector and reaching carbon neutrality.

The main findings from adaption of methods for iterative modelling of transport and energy systems are:

- Elements such as CO_2 price, electricity price and energy demand should be harmonised between the different model types.
- The temporal and spatial level can be sufficiently adjusted.
- Modal split is not directly connectable due to differences in modelling approach, so any underlying assumptions needs to be aligned.

Following is a list of the main findings from the work in the effect of transport demand on the 2030 and 2050 power system design:

- The total system cost was shown to decrease for 2030 but increased for 2050.
- While no clear patterns were observed in the changes caused by improving the temporal distribution of electric transport demand, the changes were nonetheless substantial for parts of the system.
- The changes illustrate the importance of ensuring the accuracy of the demand input data to ensure the model provides precise results.

The main findings from the qualitative methods to provide alternative insights into transport futures are:

- In the model study, the transport development is built on a number of assumptions that are characterised by a strong tie to historic trends such that e.g. a historical increase in road transport is reflected in a projected increase, as well as a 'rational economic man'-approach in which actors are assumed to respond economically rationally to market conditions.
- The qualitative studies covered a broader understanding of the systems that might form different transport futures, including aspects of environment, lifestyle, morality/fairness and health. The broader perspective in the qualitative studies may provide insights into early trends in transport development and a broader understanding of the preferences that might form transport development. Conversely, the model study was more detailed in representation of transport modes such as various vehicles and fuel types.
- When investigating transport futures, it is crucial to consider different roads to emission reductions, here characterised as Avoid, Shift or Improve strategies. Examining the model study, the emission reductions solely came from Improve strategies, for instance from electric cars replacing fossil cars or energy efficiency measures. This was highly in contrast with the qualitative studies, in which both Avoid, Shift and Improve strategies were represented, with "Avoid"-tactic such as "Flexible work conditions lead to less transportation", and Shift-tactics such as "[...] improvement of the existing path and road network to promote cycling" and "Fully electric night trains across Europe replace some air travel [...]". These differences show how model studies and qualitative studies might shed light on different reduction paths and together create a broader view on possible transport futures.
- In conclusion, qualitative studies may very well provide a valuable addition to more traditional model studies transport development, shedding light on a broader range of emission reduction opportunities, hidden or early trends in transport preferences and possibly more.

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Appendix

A. Scenario overview

In the context of the work carried out under FME NTRANS, 4 contrasting scenarios have been envisioned showing different degrees of technological and societal change and subsequently implemented in IFE-TIMES-Norway. An overview of these scenarios is presented in the Table below. For the analysis presented in Section 3.3 in this report, the Radical scenario was used. Further descriptions of the different scenarios are provided in NTRANS' Socio-technical pathways and scenario analysis report [65].

Table A-1. Overview of the differences across the NTRANS scenarios considered in IFE-TIMES-Norway, considering the values for 2050 (and demand changes between 2020 and 2050 in brackets). Source [65].

	Scenario	**Incremental (INC)**	**Technological (TECH)**	**Social (SOC)**	**Radical (RAD)**
Demand	Industry (excl. Oil & Gas)	137 TWh (+31%)	272 TWh (+105%)	106 TWh (+1%)	106 TWh (+1%)
Exogenous input	Oil & Gas	28 TWh (-63%)	28 TWh (-63%)	0	0
	Transport	NTP Road transport +37% Other transport +14%	NTP Road transport +37% Other transport +14%	Individual transport decrease with 10%. Modal shift increase bus and sea passenger by 14%. Sea freight constant (less transport but more by sea).	Individual transport decrease with 10%. Modal shift increase bus and sea passenger by 14%. Sea freight constant (less transport but more by sea).
	Buildings	84 TWh (+5%)	84 TWh (+5%)	65 TWh (-19%)	65 TWh (-19%)
El generation max potential	Onshore wind	15 GW 48 TWh	15 GW 48 TWh	8 GW 26 TWh	8 GW 26 TWh
Technology	Offshore wind	16 GW 35 TWh High cost	48 GW 207 TWh Low cost	16 GW 35 TWh High cost	32 GW 138 TWh Low cost
Transmission max potential	Domestic	20% increase	20% increase	No new	No new
	International	Allowed new	Allowed new	No new	No new
	Offshore wind	Hybrid	Hybrid	Radial	Radial
	Trade prices	Europe w/o CCS	Europe w/CCS	Europe w/o CCS	Europe w/CCS
End-use technologies					
CCS		No new	Yes	No new	Yes
Hydrogen	Electrolysers	High cost	Low cost	High cost	Low cost
	ATR with CCS	No	Yes	No	No
Industry	Hydrogen	4 TWh H_2	15 TWh H_2	4 TWh H_2	13 TWh H_2
Transport	Hydrogen	Limited	High	Limited	High
	Battery	< 90% el. vehicles	Not all trucks	< 90% el. vehicles	No limits
Flexibility		Low	Low	Medium	High
Hurdle rate	End-use	10 %	10 %	4 %	4 %
Bio energy	Biomass	Unlimited	Norwegian resources	Unlimited	Norwegian resources
	Municipal waste	As today	As today	Halved	Halved