NTRANS
Norwegian Centre for Energy Transition Strategies

Forskningssenter for miljøvennlig energi

NTRANS Socio-technical pathways and scenario analysis

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Executive summary

Under the framework of NTRANS Research Area 4 on Transition pathways studies, we have developed four energy transition pathways. The aim was to establish a systematic methodology for analysing transition pathways for Norway that could be used and further developed by the NTRANS partners and the research community at wide.

This report provides a description of the four Norwegian NTRANS transition pathways towards 2050. The ***socio-technical scenarios*** are described by driving forces behind each pathway, as well as a description of national and sectoral development in the different pathways. The qualitative descriptions of the four pathways have been discussed and evaluated to be able to quantify each pathway. The quantification of the pathways has been implemented in the energy system model IFE-TIMES-Norway and in the regional economic model REMES. Then, the two models have been used to analyse the impact of the different transition pathways on the energy system and the economy, and the results of the analyses are presented as scenario results.

The four socio-technical scenarios are based on the degree of disruption to the existing socio-technical regime and its central actors and institutions. We do so by distinguishing varying degrees of depth of change in two dimensions: socio-institutional and technological dimensions. We consider combinations of minor and major changes, which result in four pathway types: incremental, technological, social, and radical, as presented in figure I.

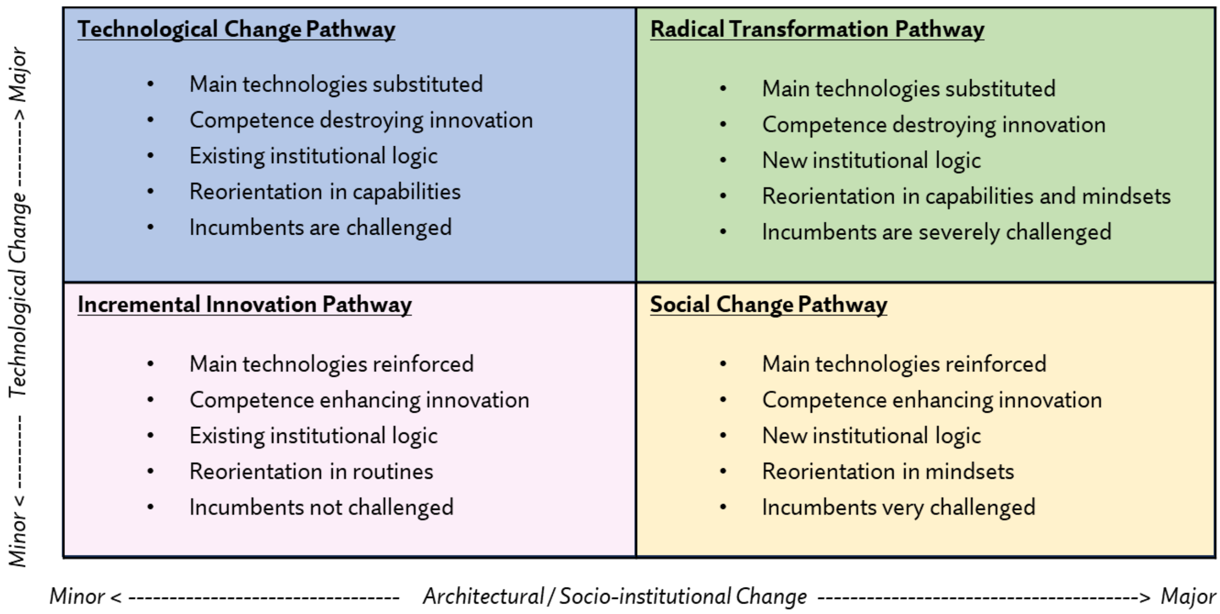

FIGURE I: TYPES OF CHANGE AT THE SYSTEM LEVEL AND ASSOCIATED CHALLENGE TO INCUMBENTS

The Incremental innovation pathway (INC) involves very limited discontinuity and is the least challenging for incumbents. The Technological Change pathway (TECH) involves deploying new core technologies to fit the existing system architecture and capabilities of incumbent actors as much as possible. The Social Change pathway (SOC) involves major socio-institutional and architectural change associated with new system functionality and service characteristics with less change in subsystem core technologies. The Radical Transformation pathway (RAD) comes with the highest degree of discontinuity and reflects a transition pattern where system architecture and institutions are transformed to fit the properties of novel core and architectural technologies.

The ***techno-economic modelling*** is carried out with the energy system optimization model IFE-TIMES-Norway, based on a quantification of the qualitative description of the four socio-technical scenarios. Important quantifications include the development of energy demand per sector, technology data and limitations on energy production and transmission, energy resources and end-use technologies. In addition, other scenario specific parameters are quantified such as CO_2 costs and targets, and both global and traded energy prices, see figure II.

«System architecture change» is interpreted as mainly having an impact on demand and central/local energy production. Scenarios with *minor* change in system architecture (TECH & INC) have an increasing economic growth, and focus on central energy production, while scenarios with *major* change in system architecture (SOC & RAD) have economic degrowth, and a focus on local solutions.

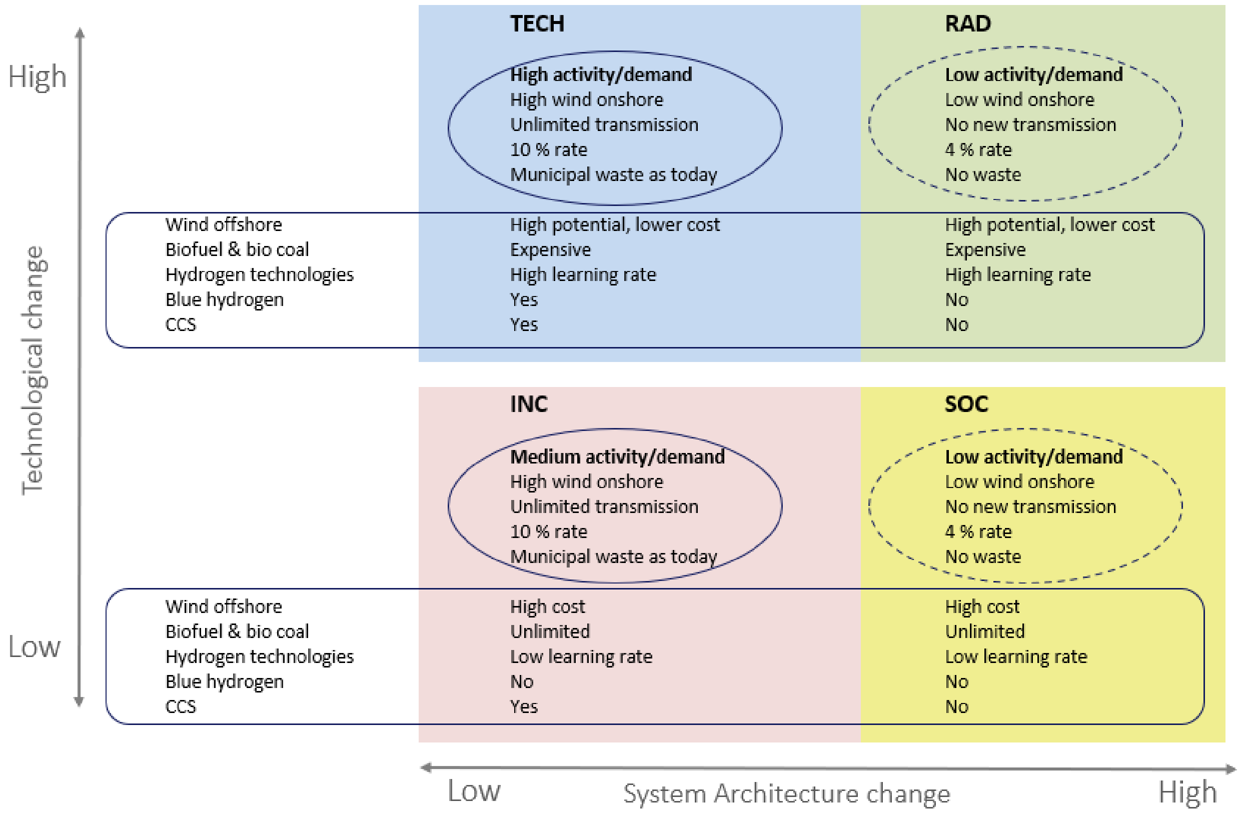

FIGURE II: OVERVIEW OF QUANTIFICATION OF THE FOUR NTRANS SCENARIOS FOR USE IN ENERGY SYSTEM ANALYSIS

One of the outcomes of the energy system analyses is the net domestic energy use, as shown in figure III. The main energy carrier is electricity, which is increasing in all scenarios; from 10 TWh/year in SOC to almost 100 TWh/year in TECH, in 2050. The use of bio energy also increases in all scenarios and is highest in the INC scenario. Natural gas is used for production of blue hydrogen for export in TECH, which increases the total use of energy by 150 TWh in 2050. Hydrogen is widely used in the transport sector in TECH and RAD, while INC and SOC only have hydrogen use in industry.

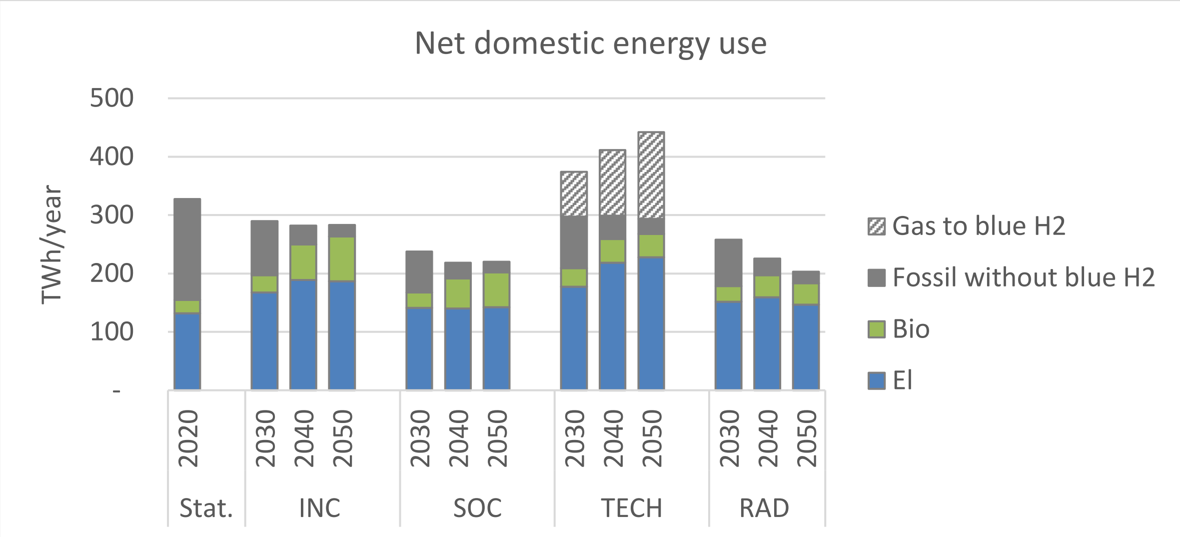

FIGURE III: FINAL ENERGY USE BY ENERGY CARRIER (TWH/YEAR)

The ***economic evaluation*** of the decarbonization scenarios is carried out with the CGE model REMES. It is based on an economic quantification of the NTRANS scenarios and starts by defining eight main aspects characterizing the development of the economy: population, productivity, technology, energy intensity, deployment of resources, export of resources, shift toward circular economy and transport development.

Compared with a reference scenario, the typical economic growth pattern of the NTRANS low carbon scenarios considers an initial reduction in GDP growth due to the decrease in value added for the oil and gas sectors. This is followed by a gradual improvement of the growth thanks to the increased availability of capitals leading to large investments in industry and services.

In comparison to the Reference scenario (REF), the INC scenario has only a modest deviation; due to the similarities of the two scenarios. The TECH scenario demonstrates an increase in value added across most sectors, thanks to the widespread adoption of hydrogen and the implementation of CCS in industry, along with the reduced capital costs resulting from divestment in the oil and gas sector. On the other hand, the different economic focus, based on societal change, characterizing the SOC and RAD scenarios, imply a reduced capacity of these scenarios to turn the tides on growth and reach a GDP level comparable to the one reached under the Reference scenario. The weaker growth displayed by these two scenarios is mostly due to the lower labour productivity and the strong phase-out of oil and gas extractions.

Demand for labour under each scenario is expected to be lower than under the reference scenario in most sectors, see figure IV. It is noticeable that the demand for labour follows the growth of the value added for nearly all sectors under the different scenarios. The TECH scenario manages to keep up with an employment level that is comparable to the one in the REF scenario, especially for sectors which are large contributors to the overall growth, such as industry or services, the two sectors which also are responsible for the largest share of employment.

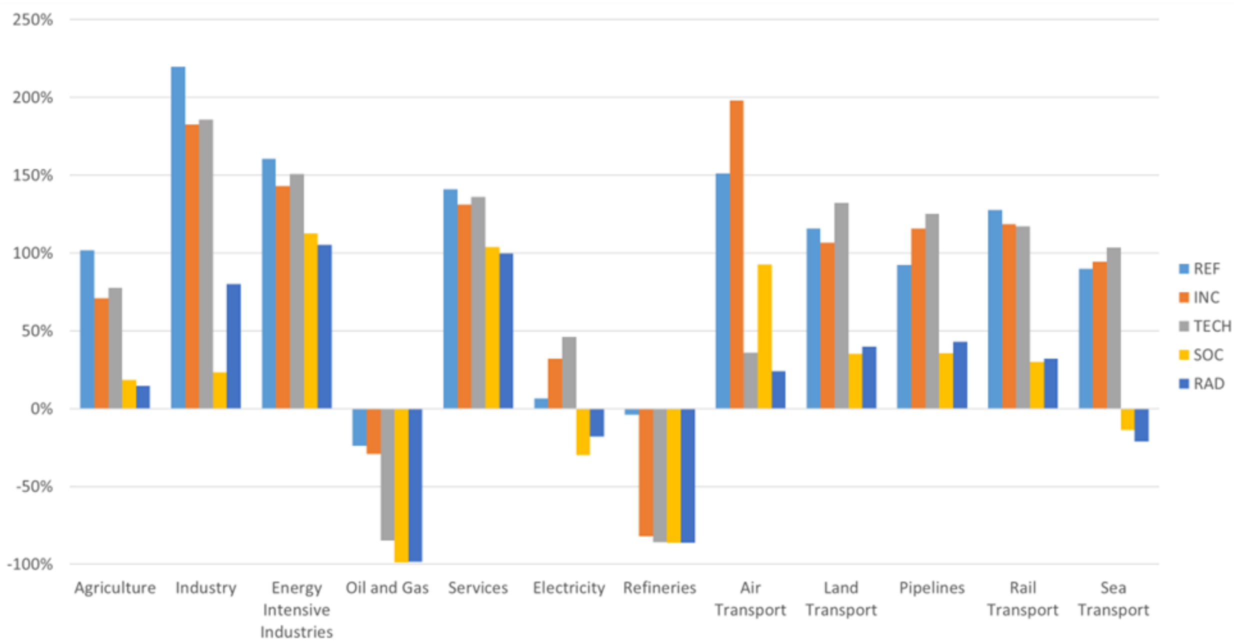

FIGURE IV: LABOUR DEMAND CHANGE COMPARED TO 2018 UNDER THE DIFFERENT SCENARIOS

1. Introduction

Under the framework of NTRANS Research Area 4 on Transition pathways studies, we have developed a ten-step approach to bridge socio-technical transition studies with quantitative energy modelling and analysis. The idea behind this approach was to establish a systematic methodology for analysing transition pathways for Norway that could be used and further developed by the NTRANS partners and the research community at wide. The ten-step methodology was developed based on an in-depth literature review, presentations and discussion of different approaches bridging socio-technical scenario studies with quantitative modelling within the management group in NTRANS.

This report describes the first three steps of this approach, namely the development of scenarios, the quantification of scenarios, and the analysis with NTRANS models. The subsequent steps are carried out in relation to selected case studies, presented in separate reports. Finally, all steps will be integrated in a scientific paper and a Policy paper.

The work with this scenario report is carried out as a collaboration between researchers in different disciplines.

The description of the socio-technical scenarios has mainly been performed by Sigrid Damman, Tuukka Mäkitie from SINTEF Digital, Allan Dahl Andersen from UiO-TIK, and Tomas Moe Skjølsvold from NTNU-KULT.

The energy system modelling has been performed by Kristina Haaskjold, Eva Rosenberg, and Kari Espegren from IFE

The economic modelling has been performed by Paolo Pisciella from NTNU-IØT.

The quantification of the scenarios has been done in close collaboration between the energy system modellers, the economic modeller, the socio-technical research team, and the user partners in NTRANS.

10-step approach

The ten-step methodology for bridging models and transitions research was developed to have a systematic approach for analysing energy transition pathways for Norway. The ten steps are as follows:

1. Develop scenarios
   - Develop different/contrasted pictures of the future based on socio-technical research
   - Describe national and sector/subsector development
   - Present and discuss scenarios with the user partners
2. Quantify the scenarios – in dialog with partners in NTRANS
3. Analysis with NTRANS models
   - Based on common assumptions for each scenario
   - Interaction between models when useful
4. Discussion of analysis results and selection of case for in-depth analysis
5. Quantitative case study – in depth-analysis
   - Based on common assumptions for each future
   - Interaction between models when useful
6. Qualitative case study
   - Socio-technical perspective on selected case
   - Focus on critical points and bottlenecks in the transition
7. Analysis/discussion: what are important measures to reduce bottlenecks in the transition?
8. Include uncertainty (short, medium, and long term) and bottlenecks in model analysis
9. Discuss policy implications from the model-based analysis and the socio-technical analysis
10. Summarize the research in a Policy paper and a result presentation

This report provides a description of the four NTRANS transition pathways towards 2050, developed for Norway. It includes a description of driving forces behind each pathway, as well as a description of national and sector development in the different pathways (Step 1). The qualitative descriptions of the four pathways have been discussed and evaluated to be able to quantify each pathway. The quantification of the pathways has been implemented in the energy system model IFE-TIMES-Norway and in the regional economic model REMES (Step 2). Then, the two models have been used to analyse the impact on the energy system and the economy of the different transition pathways, and the results of the analyses are presented as scenario results (Step 3).

2. Socio-technical scenarios

This chapter includes a description of Step 1, which consists of developing different future scenarios for Norway, based on socio-technical research. It includes a description on driving forces behind each scenario (both global and national), and a description of national and sector/subsector development in the different scenarios.

2.1 Change in socio-technical systems

Our understanding of sectors is based on the concept of socio-technical systems that consist of three types of elements: actors (e.g. firms, users, and research organizations), institutions (rules, routines, norms and visions) and technology (the technical artefact and underlying knowledge base) (Geels 2004). As these elements interact, dominant configurations known as socio-technical regimes emerge. For instance, the socio-technical regime of the transport sector consists of dominant technologies such as internal combustion engines using fossil fuels, certain dominant actors (e.g., oil companies, large vehicle producers, etc.), institutions (e.g., private ownership of cars, expected performance of the vehicle) and infrastructure (e.g., gasoline stations, motorways). Regimes are characterized by interdependencies across these elements (e.g., between the internal combustion engine and fossil fuel infrastructure, or expectations regarding the speed and refuelling need of a gasoline car), making mature sectors rather resilient to external transformative pressures (such as those resulting from climate change and decarbonisation policies). However, changes in regimes can occur as a result of a combination of external transformation pressures, performance problems within the regime (e.g., greenhouse gas emissions), and pressure from niche technologies (such as improved electric vehicles) that challenge the regime's societal function (Köhler, Geels et al. 2019). Such changes are known as socio-technical transitions, and if they result in environmental improvements, they are called sustainability transitions. Sustainability transitions can be defined as "*long-term, multidimensional and fundamental transformation processes through which established socio-technical systems shift to more sustainable modes of production and consumption*" (Markard, Raven et al. 2012).

Historically, transitions have unfolded differently across systems, time and places, giving rise to the identification of different transition patterns. Looking to the future it is also obvious that sustainability goals can be achieved in different ways. For these reasons researchers distinguish between different transition pathways or scenarios. The existence of different, and sometimes conflicting, sustainability transition pathways creates uncertainty among actors in public, business, and civic domains.

2.2 Pathway types and actor preferences

Drawing on recent research in NTRANS (Andersen, Markard et al. 2023) we suggest identifying distinct transition pathways and scenarios based on the degree of disruption to the existing socio-technical regime and its central actors and institutions. We do so by distinguishing varying degrees of depth of change in two dimensions: socio-institutional and technological dimensions. We consider combinations of minor and major changes in these dimensions, which result in four pathway types: incremental, technological, social, and radical.

The incremental change pathway involves minor changes in both technological and socio-institutional dimensions. The technological pathway is associated with major change in the technological dimension, but minor change in the socio-institutional dimension. The social change pathway involves only minor change in the technological dimension but major socio-institutional change (Henderson and Clark 1990, Tushman and Murmann 1998). The radical change pathway implies major changes in both dimensions. Major changes generally challenge actors inter alia in terms of assets, business models, and value networks with customers and suppliers. Hence, some transition pathways require deep changes in socio-institutional factors (e.g., lifestyles and values) and shallow change in technology, while other pathways mainly involve deep changes in technologies (cleaner products) and limited change in the socio-institutional dimension. We call deep socio-institutional changes architectural changes in systems (Geels and Turnheim 2022, Andersen, Markard et al. 2023).

To understand how pathways and organizational challenges are related, we use a configurational perspective on actor reorientation (Gavetti and Rivkin 2007, Geels 2021, Geels and Turnheim 2022). This perspective views organizations as hierarchical configurations of cultural-cognitive elements, capabilities, competence, assets, and organizational routines and habits (Gavetti and Rivkin 2007, Geels 2020). Actor reorientation, for example the diversification of established companies from dominant technologies to niche technologies, can occur at different levels, ranging from moderate to deeper levels of change (Geels 2021, Geels and Turnheim 2022).

The challenges posed to incumbents in each pathway correspond to the varying depths of reorientation identified in the literature. The four pathways and the implied level of reorientation in each pathway are as follows:

1. *Incremental Innovation Pathway:* Minor changes in technological and socio-institutional dimensions require reorientation at the level of organizational routines and habits, which can be managed without major changes in capabilities, strategy, or firm identity. It could involve making existing technologies more sustainable through add-on innovations such as using biofuels in existing internal combustion engines. This is the least demanding type of reorientation (Tushman and Anderson 1986) (Henderson and Clark 1990, Geels 2014).

2. *Technological Change Pathway:* Radically different technologies diffuse while changes in socio-institutional factors are minor (Smith and Raven 2012, Geels, Kern et al. 2016). For example, shifting from gasoline to electric vehicles can be done without fundamentally changing the overall configuration of the transport system (e.g., mobility practices, business model of automakers, and modes of transportation remain the same). This pathway requires that incumbents change core capabilities and resources and is thus more demanding. It involves competence-destroying innovation in technologies (Tushman and Anderson 1986), for example, steam engines making sail ships obsolete in the past, or electric vehicles potentially making internal combustion engines obsolete in cars in future. Incumbents typically respond by exploring and building new capabilities, resources, and engage in organizational change and strategic adjustments (Fiol and Lyles 1985, Henderson and Clark 1990) (Tushman and Romanelli 1985).

3. *Social Change Pathway:* Technologies only undergo minor changes, but how they interact changes more fundamentally. For example, less overall transport, shared mobility, and modal shifts towards more public transport and/or walking and cycling could foster a major sustainable shift in transportation systems without changing the internal combustion engine as a main technology. This shift would require major changes in socio-institutional factors, e.g., new travel behaviours to achieve shifts in inter-modal transport, for growing sharing of cars and bikes, and for generally move to seeing transportation as a service. Shifts in system architecture are challenging for incumbents because they require reorientation at the level of organizational identities and mindsets that underpin business models and strategy and are aligned with the institutional logic of the system architecture (Tushman and Romanelli 1985, Henderson and Clark 1990). This is an even more challenging type of reorientation for incumbents.

4. *Radical transformation pathway:* Major changes are made in both technological and socio-institutional dimensions. For example, a shift from decentralized (i.e., individual) and gasoline-fuelled transportation towards centralized (i.e., collective and shared) and electrified transportation. This requires the most radical form of reorientation, which involves building new capabilities and resources and changing organizational identities and business models (Tushman and Romanelli 1985, Geels 2014).

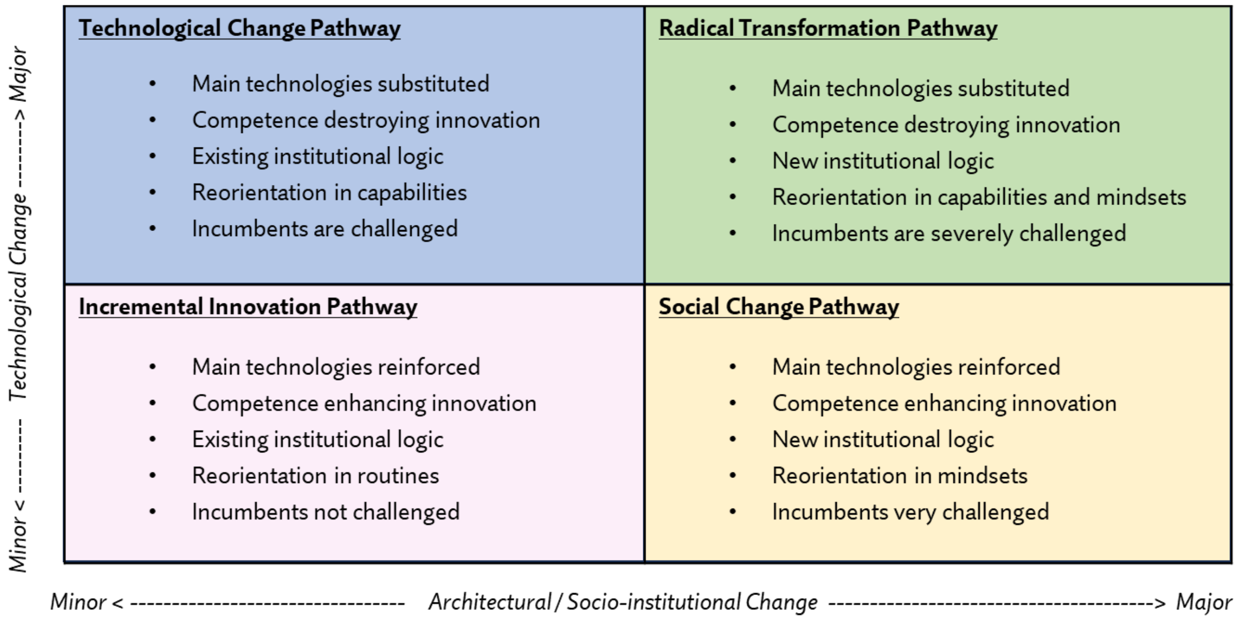

FIGURE 1: TYPES OF CHANGE AT THE SYSTEM LEVEL AND ASSOCIATED CHALLENGE TO INCUMBENTS

2.3 Exogenous pressures

Different pathways may also be associated with different transformative pressures at a wider societal level. Such pressures may be related to factors that change only slowly, such as climate change, long-term trends in terms of demography or industrialisation, or to rapid external shocks such as war and economic crises. (Geels and Schot 2007), discuss how such exogenous pressures may vary and e.g., take the form of gradual, regular change, sudden shocks, disruptive change mainly on one dimension, or cascading disruption on multiple dimensions. These wider system interactions are actualised by the coronavirus pandemic and the war in Ukraine, and therefore to some extent considered in the overarching pathways defined in NTRANS.

2.4 Socio-technical pathways defined in NTRANS

Following the 8-step approach of (Geels, McMeekin et al. 2020), we distinguish between socio-technical scenarios (STSc), as the result of dialogue between a socio-technical perspective and quantitative modelling, and ideal-type transition pathways, based on a combination of aspects from existing socio-technical pathway typologies. This section presents the qualitative storylines for four alternative transition pathways developed in NTRANS, based on the conceptual framework and typologies outlined above.

Four pathways have been identified: Incremental Innovation, Technological Change, Social Change and Radical Transformation. The Incremental innovation pathway involves very limited discontinuity and is the least challenging for incumbents. The Technological Change pathway involves deploying new core technologies to fit the existing system architecture and capabilities of incumbent actors as much as possible. The Social Change pathway involves major socio-institutional and architectural change associated with new system functionality and service characteristics with less change in subsystem core technologies. The Radical Transformation pathway comes with the highest degree of discontinuity and reflects a transition pattern where system architecture and institutions are transformed to fit the properties of novel core and architectural technologies.

Each pathway is associated with different degrees of disruption to the status quo and can challenge actors in terms of assets, business models, and value networks with customers and suppliers.

Incremental Innovation pathway (INC)

The Incremental Innovation pathway is characterized by gradually increasing pressure and incremental innovation. The population is increasing steadily, in line with current projections, and the focus on economic growth remains. The current climate goals and climate and energy policies are continued. Technological progress takes place only gradually, following the current direction and pace of change. There are no major leaps in the development of radical technologies, e.g., in battery or fuel cell technology, or in terms of hydrogen storage or ammonia for energy. Resources used for energy production still include global oil and gas, renewable energy, and biomass, and there is an increasing demand for energy and food. However, there is also increasing energy efficiency, linked to further development of existing technologies.

Transport demand is also increasing, in accordance with the National plan for alternative fuels in transport (Ministry of Transport 2021). For road transport, the focus remains on electrification, supplemented with biofuels for heavy-duty transport. Rail transport is electrified. In shipping there will be a strong focus on improved energy efficiency, and a substantial share of public tendered passenger transport and other small, short-route vessels will be electrified. Other segments will still deploy conventional fuels, with an increasing share of biofuels, linked to the biofuel mandate. Meanwhile, there are ongoing pilots around e.g., hydrogen, and the proposal to allow liquid biogas as a 'zero emission' fuel in a transition period, in order to realise the ambition to reduce emissions in the world heritage fjords. However, these fuels are not expected to break into mainstream use. Aviation will primarily use conventional fuels, but will have an increasing share of biofuel blend-in, however there will be further piloting of battery-electric solutions for small and short-range flights.

Decarbonisation of industry will for a large part depend on energy efficiency measures and electrification, and hydrogen. Since the core technologies are reinforced, many of the existing incumbents in the energy and industry sectors are able to keep a central role. A potential increase in domestic and international transmission capacity, including hybrid wind connections to attract investments in the North Sea, is foreseen. Potential Norwegian niches in this pathway include battery-electric ships, biofuels from aquaculture and forestry, and the development of value chains for algae and perennial grasses to produce advanced biofuels.

The environmental behaviours of citizens do not change much. Despite increasing awareness, incentives do not get much stronger, and people largely stick to the lifestyle they have today in terms of degree and quality of consumption, travel and energy use. On the other hand, there are potential controversies and conflicts to consider, linked to land use and sustainability concerns, for instance in terms of novel renewable energy production, including biomass use for biofuels vs. food production and ecological considerations. Participation may also be contingent on capital and technology, raising issues of distributional and recognitional justice as discussed in energy justice literature. Institutionalization and entrenchment of transport, energy, and flexibility poverty are also potential issues to address.

Technological Change pathway (TECH)

The Technological Change pathway is associated with a stronger and more sudden pressure for change at the broader societal level, together with more radical change technologies. This leads to innovation in new core technologies, but less so in institutions and lifestyle. Here, too, we assume that the population continues to grow as projected. The existing institutional logic remains. The national economy continues to grow, and energy demand increases. However, the sudden increase in exogenous pressure, which easily could be associated with increasing global conflict level and energy crisis (such as the war in Ukraine), is assumed to hit when the development of new niche technologies has reached a high enough level of maturity to break through and lead to accelerating technological change. To meet the increasing demand for energy, the resources used still include global oil and gas, which also is used as feedstock for blue hydrogen production. However, various types of renewable energy, including floating offshore wind, continue to grow, and due to technology development, there is also an increase in biofuel production based on Norwegian resources.

This pathway sees a strong increase in the maturity and availability of alternative technologies and energy carriers such as hydrogen, ammonia, batteries, and carbon capture and storage (CCS). This opens several routes for decarbonisation of existing industry, e.g., not only electrification but also use of hydrogen and CCS.

Transportation demand increases, leading to major technological change towards zero-emission technologies and energy carriers such as batteries, hydrogen, and ammonia, as well as CCS. The different modes of transportation are affected differently, with batteries dominating for private cars, while solutions for heavy-duty vehicles include both batteries and hydrogen/fuel cells. Rail transportation also shifts towards electrification, while shipping utilizes ammonia, hydrogen, and batteries, as well as biofuels and fossil fuels. In aviation options for increased use of biofuel, battery-electric systems for short and light flights, as well as hydrogen-powered solutions are available.

As part of this development, the large incumbents in the energy and industry sectors increasingly find themselves challenged by new technology providers and are forced to reorient in terms of capabilities, towards renewable energy and new energy carriers. This change is associated with development of increased transmission capacity, both domestically and internationally. Norway has niches in hydrogen, electrification, CCS, and hydrogen maritime technologies, which present an opportunity for the country to lead in these areas. As the low-carbon transition is largely enabled by technological innovation and substitution, social change in e.g., lifestyles are limited, also in this scenario. However, potential societal issues may arise, such as land use, contestation of sustainability, legitimacy, and acceptance issues. Participation in this shift may also depend on capital and technology, raising issues of distributional and recognition justice, as discussed in energy justice literature. There is also a potential for institutionalization and entrenchment of transport, energy, and flexibility poverty.

Social Change pathway (SOC)

The Social Change pathway involves strong pressure and institutional changes to focus on sustainable well-being rather than economic growth. This may for example be linked with global conflict and unstable energy markets, leading to increased focus on preserving scarce resources and maintaining energy security at national and local levels. Population growth may decrease, due to less immigration. Architectural structures, rather than technologies, are radically changed. We assume this happens through social innovation and circular economy, as well as innovation in technologies such as ICT-based smart solutions that enable new forms of integration, decentralisation, and flexibility, both within the present energy system and between the energy system and other sectors. Moreover, local production networks and symbiotic innovations such as Industry 5.0 and automatization become prevalent, reducing the need for global transport of goods.

Since the core technologies are not substituted by new solutions to any large extent, existing emission reduction solutions, such as technologies to improve energy efficiency, biofuels, battery-electric cars and small vessels will be more widely implemented. Power generation experiences only limited growth, and decentralised renewable energy (solar PV, onshore wind) and community-based solutions, such as energy cooperatives, will be important. Since there will be a lack of new zero-emission technologies, the existing incumbents in the industry can be hard hit by increasing CO_2 taxes and other policy measures. Some of the most energy-intensive industry based on fossil fuels may struggle and subside, while the shift towards circular economy and smart, ICT-based solutions will give unprecedented growth in other sectors, e.g., generating value from waste, and give rise to new services, such as data centres, connectivity, and flexibility services.

Since this pathway includes radical social change towards sustainability, we assume that Norwegian oil and gas production will slow down and be shut completely by 2034, in line with the current position of several NGOs and some politicians, which amongst other are based on influential analyses by the Tyndall Centre for Climate Change Research (Calverley and Anderson 2022). There is less increase in energy demand, with a shift towards circular economy and localization of production. Thus, and also due to less development of radical technologies, no new transmission capacity is included in this pathway. Being mature from a technological point of view, CCS is assumed to play a role in energy transition, but renewable energy and biofuels will be the main resources.

Transport needs are reduced, with increased digitalization, optimization, and integration of transport solutions. Public transport, biking and walking, car sharing, and mobility-as-a-service are utilised more, and the number of privately-owned cars is reduced drastically, as a result of changing attitudes and behaviours as well as enabling technologies, e.g., sharing platforms, autonomy, and flexibility solutions. Rail transport is emphasized with electrification, while shipping increasingly relies on biofuels and electrification. Air transport sees a significant decrease in demand and the possibility to reduce emissions from aviation will be by the introduction of more biofuel solutions.

Potential Norwegian niches in this pathway include smart transport solutions and digitalization. However, there may be resistance from the regime, such as fossil fuel incumbents, car dealers, etc. The Social Change pathway includes increased environmental consciousness which also leads to major changes in the population's lifestyles, including less consumerism and more focus on welfare and self-sufficiency. Societal issues that may arise include discussions on phase-in vs. phase-out policies and political procedures and legitimacy. While this pathway is less likely to reinforce existing divides, it may produce new and more resourceful “losers” such as incumbent actors with more resources to fight back. The need for cultural change, adaptive living standards, and change in land use are also important considerations.

Radical Transformation pathway (RAD)

Finally, the Radical Transformation pathway is characterized by an external shock, which triggers cascading disruption on multiple dimensions. Radical change involves both major technological and social change. Similarly, as in the social change pathway, the economy will shift its focus to sustainable development and well-being. However, global collaboration is expected to decrease, and regionalization will become more prominent (in line with the overarching assumptions behind Statkraft's Low Emission Scenario (Statkraft 2022)). Social innovation and innovation in system architecture (enabling e.g., circular economy, integrated and flexible power systems, and local production) are coupled with innovation in core innovations.

Like the Technological Change pathway, the Radical Transformation pathway sees a strong increase in maturity and availability of alternative technologies and energy carriers such as floating offshore wind, hydrogen, ammonia, batteries, and CCS. This opens several routes for decarbonisation of existing industry, e.g., not only electrification but also use of hydrogen and CCS. In addition, there is some advanced bioenergy/biofuel production, based on Norwegian resources. This combination of core technology and architectural change (including e.g., flexibility technologies) enables new types of transport and energy production and use patterns. Resources will mainly consist of renewable energy. As there is more regionalisation, today's transmission capacity will likely be sufficient and only radial offshore wind connections are allowed. Oil and gas production is phased out by 2050, thus there is no blue hydrogen production in Norway.

In this pathway, as in the social change pathway, the demand for energy and food will stabilize, due to more sustainable lifestyles and increased focus on self-sustenance and circularity. There will be reduced demand for transport due to local production and less travel, as well as changing land use and densification in cities. New green mobility patterns, digital solutions, and automatization will be used to satisfy social and experiential needs, such as video conferencing and virtual reality. The road sector will see less transport, more shared electric vehicles, and increased use of public transport, bikes, and walking. Rail transport will see increased electrification, while shipping will use less fuel and move towards green hydrogen-based fuels and electrification, although some biofuel still is needed. Modal shift from road to rail and sea transport will increase, while air transport will decrease, with electrification and hydrogen emerging as main alternatives, in addition to biofuel.

Incumbents are severely challenged, and potential Norwegian niches in the Radical Transformation pathway include renewable hydrogen, Industry 5.0, CCS, and smart & digital solutions. However, there will be potential societal issues to address, such as land use, living standards, and increasing international inequalities. This pathway could create fertile soil for political populism, xenophobia, and other related challenges.

3. Quantification of scenarios

This chapter presents how the qualitative descriptions of the scenarios are understood in the energy system analyses and the assumptions made to use these four scenarios in the techno-economic and regional economic modelling. The results of the analyses are then presented in chapter 4 “Scenario results”.

3.1 Techno-economic modelling

3.1.1 Overview

The techno-economic modelling is carried out with the energy system optimization model IFE-TIMES-Norway (see description in Appendix A). The qualitative description of the four scenarios must be quantified to be used in analyses with the energy system model. Important quantifications are needed of the development of energy demand per sector, technology data and limitations on energy production and transmission, energy resources and end-use technologies. In addition, other scenario specific parameters must be quantified such as CO_2 costs and targets, and both global and traded energy prices. These subjects are described in the following and an overview of the differences between the scenarios is presented in Table 1.

The «System architecture change» is interpreted as mainly having an impact on demand and central/local energy production. Scenarios with *minor* change in system architecture (TECH & INC) have an increasing economic growth, and focus on central energy production, while scenarios with *major* change in system architecture (SOC & RAD) have economic degrowth, and a focus on local solutions.

The projection of energy service demand of industry, buildings and transport will be further developed in a parallel NTRANS collaboration project. The present energy service demand projections are used here and will be replaced by new projections in future analyses.

TABLE 1: OVERVIEW OF THE DIFFERENCES BETWEEN THE SCENARIOS IN IFE-TIMES-NORWAY, ALL NUMBERS PROVIDED FOR 2050 (DEMAND CHANGE 2050 VS. 2020 IN BRACKETS.) SEE TEXT FOR DETAILS.

	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	5 GW 15 TWh	5 GW 15 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	Domestic	20% increase	20% increase	No new	No new
max potential	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 H2	15 TWh H2	4 TWh H2	13 TWh H2
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

3.1.2 Energy service demand

Industry

The industry sector is divided into 10 sub-sectors and up to three end-uses: heat, specific electricity and raw material. In the energy system model IFE-TIMES-Norway, the industry sector includes electricity generation in offshore oil and gas production (capturing the CO_2-emissions in the model). For simplicity, industry also includes agriculture and the construction sector. Production of hydrogen for transportation is not modelled as an industry sub-sector, but as a conversion process delivering the hydrogen needed for different transportation modes. Use of hydrogen in industrial processes is modelled as a technology option in each industry sub-sector where it is possible to use.

The demand in 2018 and 2020 is calibrated with the energy balance and the emission balance. In the total demand, the use of raw material with CO_2-emissions is also included, to calibrate the model with actual CO_2 emissions.

The development of demand is considered for each sub-sector in the different scenarios. *Minor* change in system architecture is interpreted as that in current trends and expectations continuing towards 2050, resulting in an increased energy demand for industry production. Due to the reduced economic activity corresponding to *major* change in system architecture, the industry demand projections are assumed to be lower than current expectations. With *Minor* change, it is assumed that there will be no phase-out of Norwegian oil and gas sector, but a reduction in line with Perspektivmeldingen 2021 (Norwegian Ministry of Finance 2020), whereas with *Major* change, an oil and gas phase-out will occur. This will both impact the electricity that is used to electrify the Norwegian continental shelf and the total Norwegian CO_2 emissions. In the SOC scenario, no oil and gas extraction are assumed from 2034 (linear decrease from 2025) and in the RAD scenario the phase-out occur by 2050 (linear decrease from 2030).

The SOC and RAD scenarios have the same development in industry, with demand kept constant from 2025 to 2050. Known industrial investments or shutdowns until 2025 are included in the demand, but no new industry activities are included.

The INC scenario has an increased energy demand in mainland industry. In combination with reduced activities in oil & gas extraction, this results in an increase of electricity specific demand and a decrease in total energy demand, as shown in Table 2. The development in oil & gas extraction is in line with the expectations of "Perspektivmeldingen 2021", where the activity is reduced to one-third in 2050 relative to the peak activity in 2024 (falling from 256 mill. Sm3 o.e. in 2024 to about 83 mill. Sm3 o.e. in 2050) (Norwegian Ministry of Finance 2020). The development of other sub-sectors is our estimation, based on different projections of energy demand, such as (NVE 2020, Process 21 2021, Statnett 2023). It can be summarized as:

- Aluminium: One new production line
- Other metal production: two more production lines
- Chemical industry: four more production lines
- New activities: battery factories and datacentres with a total electricity use of 20 TWh in 2050
- Mineral: constant at today's level
- Light industry: constant at today's level
- Agriculture: constant at today's level
- Construction: constant at today's level

The industrial activity in the TECH scenario is even higher than in the INC scenario. One more aluminium plant is included, as well as two more plants for other metal production. In the chemical industry (incl. silicon production), the activity is at the same level in the INC and TECH scenarios with a total of four new plants. The highest increase of power demand is expected in new industrial activities such as battery factories, synfuel production for export and data centres. The energy demand for synthetic fuels for export is estimated to 10 TWh, and more battery factories or other plants is estimated to 35 TWh, in total 45 TWh more electricity demand. The TECH scenario also includes export of blue hydrogen, modelled as 70 TWh hydrogen from 2040 and 100 TWh in 2050. The light industry, agriculture and construction are estimated to increase by 29% until 2050.

TABLE 2: ENERGY SERVICE DEMAND OF TOTAL ENERGY AND SPECIFIC ELECTRICITY IN INDUSTRY, 2020 AND IN 2050 IN THE FOUR SCENARIOS, TWH/YEAR

	Total				Electricity specific use			
	2020	INC	TECH	SOC & RAD	2020	INC	TECH	SOC & RAD
Aluminium	32	39	44	34	22	28	32	24
Other metals	16	20	20	16	5	6	6	5
Chemicals	20	23	23	20	8	10	10	8
Wood	17	17	17	17	4	4	4	4
Minerals	4	4	4	4	1	1	1	1
Light	10	10	13	10	4	4	5	4
Agri&Construction	4	4	5	4	3	3	4	3
Petro	69	28	28	-	9	9	9	-
New	1	20	46	1	1	20	46	1
H2 Export	-	-	100	-			5	
Total	**173**	**165**	**299**	**106**	**56**	**85**	**121**	**49**

The load profile of all industry sub-sectors, besides light industry, is assumed to be flat, i.e., continuous operating time during the entire year. In light industry, a daily load profile is used, assuming no seasonal variation. The profile is equal to that of commercial buildings.

Buildings

Energy efficiency in buildings involves parameters that influence the final energy consumption of the Norwegian building stock. *Minor* change in system architecture implies that the trends of today continues towards 2050. *Major* change in system architecture implies that the final energy consumption in buildings is lowered compared to base through the following measures: a more extensive upgrade of the building stock and a smaller living area per person, either through smaller houses or an increase in multi-family houses.

In the INC and TECH scenarios, the energy demand of buildings (both dwellings and non-residential buildings) is based on a continuation of current trends regarding the energy efficiency level of the building stock (Sartori, Lindberg et al. 2022). Energy efficiency is not pushed, but it is carried out whenever economically profitable. A small increase in the energy upgrading of renovated buildings is assumed and new constructions after 2030 have a passive house standard. The building stock is assumed to grow by 17% from 2020 to 2050, where 29% are constructed, 26% are renovated and 45% remain unchanged up to 2050.

In the SOC and RAD scenarios, energy efficiency plays an important role. For the time being, this is simplified as a decreasing demand of 15 TWh in 2030 in the existing building stock. In future analyses, this will be modelled more detailed using different energy efficiency measures possible to invest in, with costs, lifetimes, and potential per measure.

The energy service demand projection is summarized in Table 3. The end-use is divided in demand for electricity that cannot be substituted by other energy carriers (el.spec.) and in "heat" which is energy demand for space heating and domestic hot water. The building types are divided into single-family houses which are small, individual dwellings, multi-family houses, which are apartments, and non-residential buildings which are all other types of buildings. Each building type is further divided into existing (in 2020) and new buildings, built after 2020.

TABLE 3: ENERGY SERVICE DEMAND PROJECTION OF BUILDINGS IN THE FOUR SCENARIOS (TWH/YEAR)

Building type		End-use		INC & TECH		SOC & RAD	
			2020	2030	2050	2030	2050
Single-family	Existing	El.spec.	8.4	7.9	6.7	7.6	6.4
		Heat	32.8	30.5	24.8	26.0	18.8
		Total	41.1	38.4	31.4	33.7	25.2
	New	El.spec.	-	0.8	2.4	0.8	1.4
		Heat	-	2.0	4.8	1.7	2.7
		Total	-	2.9	7.2	2.5	4.1
Multi-family	Existing	El.spec.	1.8	1.7	1.6	1.7	1.5
		Heat	5.1	4.9	4.4	3.9	3.0
		Total	6.9	6.6	5.9	5.6	4.5
	New	El.spec.	-	0.5	1.5	0.4	2.1
		Heat	-	1.0	2.7	0.8	3.7
		Total	-	1.5	4.1	1.3	5.8
Non-residential	Existing	El.spec.	16.6	15.8	14.2	14.2	12.1
		Heat	15.3	14.4	12.7	10.7	7.6
		Total	31.9	30.1	26.9	24.9	19.6
	New	El.spec.	-	1.4	3.7	0.7	3.6
		Heat	-	0.9	2.0	0.5	1.8
		Total	-	2.3	5.8	1.2	5.4
Residential	All	El.spec.	10.1	10.9	12.1	10.6	11.4
		Heat	37.9	38.4	36.6	32.5	28.1
		Total	48.0	49.3	48.7	43.1	39.6
Non-residential	All	El.spec.	16.6	17.2	18.0	14.9	15.6
		Heat	15.3	15.3	14.7	11.2	9.4
		Total	31.9	32.5	32.7	26.1	25.0
Buildings	All	El.spec.	26.8	28.1	30.1	25.5	27.1
		Heat	53.1	53.7	51.3	43.7	37.6
		Total	79.9	81.8	81.4	69.2	64.6

Transport

The transport demand involves parameters that influence the final energy consumption of the Norwegian transport sector. *Minor* changes imply that today's trends continue towards 2050. Consequently, the modelling assumptions on the future transport demand will be based on the National Transport Plan (NTP) (Ministry of Transport 2021). *Major* changes imply that the demand for energy services from transport is lowered in two different ways. First, through a more extensive use of local goods and services, the demand for goods transport is lowered. Second, through more environmental awareness, there is a modal shift from personal car transport to the use of walk, bike, and public transport.

Road transport in IFE-TIMES-Norway includes passenger cars, vans, trucks, and buses. The demand for heavy-duty trucks is divided into three segments, as its size and daily milage are central parameters for energy consumption and feasibility of different propulsion systems. The segments are short distance trucks (driving less than 300 km/day), small, long-distance trucks (>300 km/day, <50 ton gross weight) and large long-distance trucks (>300 km/day, >50 ton gross weight).

The demand towards 2050 is based upon the projections made in the national transport plan (NTP) 2022-2033. Only national data of demand for buses in passenger-km are available from NTP, and therefore data from TØIs BIG-model on vehicle-km is used for the base year (Fridstrøm and Østli 2016) . The division on geographical regions is based on population per region. The projection is based on relative change in passenger-km from NTP.

The total heavy freight transport is based on data from NTP 2022-2033 and is divided in the three truck classes of IFE-TIMES-Norway as described in the previous paragraph. The division of data per region and the relative development from 2018 to 2050 is based on county data of NTP 2022-2033.

Apart from road transport, rail, sea, and air transport are considered. In addition, a category gathering the rest of transport demand is included in “other transport”. Demand is modelled as an energy demand (GWh/year) in these categories.

Energy use of domestic air transport in the base year is divided in the five regions based on population in 2018. Development in passenger-km in NTP 2022-2033 is used for the demand projection of air transport. Sea transport is divided in passenger transport, fishing, and other sea transport. The projection of passenger sea transport is based on the development of passenger-km in NTP 2022-2033. For the two other sea transport categories, the total development of freight transport by sea is used. The projection of rail transport is 50% based on development of passenger transport and 50% on freight transport. The rest category is assumed to develop according to the increase in population of Statistics Norway 2020 (MMMM alternative).

In the SOC and RAD scenarios, transport demand is decreasing and a modal shift from individual to public transport takes place for passenger transport and from road to sea and rail for freight transport. This is quantified as a 10% decrease in demand of vehicle-km for individual road transport (cars, vans, and trucks) and an increased use of buses, train, and passenger ships by 14% (in line with the population growth of (Statistics Norway 2022) MMM alternative). The freight ships are not increased since this category also include supply ships of offshore oil and gas extraction and this activity is decreasing. The share of transport by sea and rail is higher in the SOC and RAD scenarios compared to the INC and TECH scenarios, where a higher increase in road freight transport is assumed. This is in line with the target of a modal shift from road to sea and rail as discussed in the qualitative description of the scenarios.

As part of the 10-step methodology for transition pathways analysis, we are performing an in-depth study of the maritime sector. The study will be documented in a separate report, and the results will enable improvements of the modelling and analysis of the maritime sector. This improved modelling of the maritime sector will be included in future scenario analysis.

The demand projections of transportation are summarized in Table 4. It is divided in road transport and non-road transport due to different units in IFE-TIMES-Norway. Demand of road transport is given in vehicle-km per year and non-road transport is – for simplicity – modelled as an energy demand.

Table 4: Demand projection of transportation in the four scenarios (billion-vehicle-km for road transport and TWh/year for non-road transport)

		INC & TECH				SOC & RAD			
	2018	2020	2030	2050	2050 vs. 2018	2020	2030	2050	2050 vs. 2018
Road transport (billion-vehicle-km)	**45.1**	**46.3**	**52.5**	**61.7**	**137 %**	**45.1**	**45.2**	**40.8**	**90 %**
Cars	35.1	36.0	40.1	45.1	128 %	35.1	35.1	31.6	90 %
Vans	7.3	7.6	9.4	12.7	174 %	7.3	7.3	6.6	90 %
Small trucks	0.51	0.49	0.41	0.37	72 %	0.51	0.51	0.46	90 %
Large trucks, short distance	0.77	0.82	1.02	1.44	186 %	0.77	0.77	0.70	90 %
Large trucks, long distance	0.77	0.82	1.02	1.44	186 %	0.77	0.77	0.70	90 %
Buses	0.57	0.58	0.60	0.62	108 %	0.59	0.65	0.73	114 %
Non-road transport (TWh)	**21.6**	**21.9**	**23.0**	**24.6**	**114 %**	21.6	22.2	22.3	103 %
Air	4.9	4.9	5.1	5.3	109 %	4.9	4.9	4.4	90 %
Passenger ships	3.5	3.5	3.6	3.5	101 %	3.5	4.0	4.5	128 %
Fishing ships	2.7	2.8	3.0	3.2	116 %	2.7	2.7	2.7	100 %
Other ships	4.7	4.8	5.1	5.4	116 %	4.7	4.7	4.7	100 %
Rail	0.7	0.8	0.9	1.2	163 %	0.7	0.8	0.9	128 %
Other mobile transport	5.1	5.2	5.4	6.0	117 %	5.1	5.1	5.1	100 %

3.1.2 Technology data and limitations

Energy generation and transmission

The electricity generation modelled in IFE-TIMES-Norway can be supplied from several energy sources, including hydropower, onshore and offshore wind power and photovoltaic (PV). While hydropower is a mature technology with limited potential for new deployment in Norway, the future technology development and expansion potential of wind and solar is uncertain. Similarly, this uncertainty applies to other technologies, such as hydrogen, CCS and large-scale storage systems. Aligning with the scenario's description, different assumptions on technology parameters have been defined. *Minor* change in technology implies that current trends of today continues with a highly centralised energy production. *Major* changes imply that local energy solutions are favoured, including local electricity generation by building applied PV and hydrogen production. Local energy solutions also include local energy storage through e.g., stationary batteries and hydrogen tanks. In terms of system architecture change, *major* involves a larger focus on protecting nature and preventing interventions. Consequently, limitations on onshore wind and national transmission grid expansion are enforced, while Norwegian hydropower that is protected by law is untouched. On the other hand, *Minor* allows new onshore wind power development and national transmission lines if it is considered a cost-efficient solution.

In the SOC and RAD scenario, new onshore wind power is restricted to already applied concessions, as well as reinvestments in existing plants. The total expansion potential is 5 GW, corresponding to 15 TWh production. New potential for offshore wind is driven by the degree of technology change, with INC and SOC having limited potential of 16 GW by 2050. In these two scenarios, high cost of new development is assumed. Contrarily, TECH and RAD assume a high expansion potential of up to 48 GW by 2050, with lower cost of investment (see Figure 2). The expansion potential is based on the Norwegian target of 30 GW by 2040. In terms of new transmission grid development, INC and TECH assume high transnational interactions to support the green transition in Europe and allow for new value creation in Norway through increased exports.

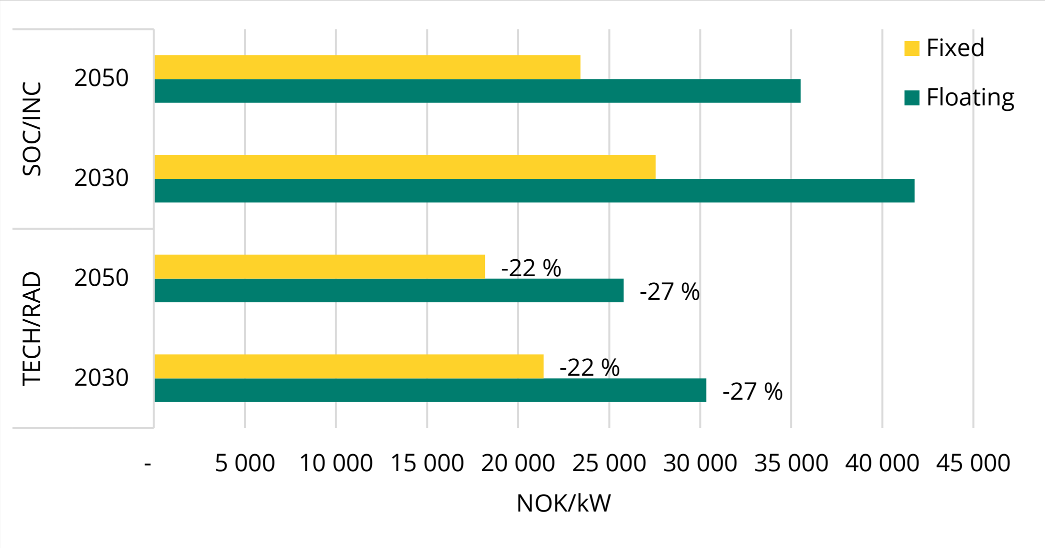

FIGURE 2: INVESTMENT COST OF FLOATING AND BOTTOM-FIXED OFFSHORE WIND IN 2030 & 2050, NOK/KW

The potential for new international transmission capacity is based on assumptions from ENTSO-E's Ten-Year Network Development Plan 2020. Moreover, national transmission capacity is allowed to increase by 20% from today's capacity. In the SOC and RAD scenarios, no new national or international transmission capacity is allowed. The assumption is rooted in the focus on protecting nature, as well as prominent regionalization with less global collaboration. The transmission capacity from offshore wind regions is aligned with the transnational transmission assumptions, in which hybrid connections are assumed for the INC and TECH scenarios, while export of offshore wind production is limited to radial connections in SOC and RAD. With hybrid connections, offshore wind regions located in the North Sea can be connected to Denmark, Germany, the Netherlands, and the UK if considered cost efficient. With radial connections, offshore wind production is only connected to Norway, and in principle used to supply the Norwegian energy demand.

Further, the Norwegian electricity price is highly dependent on the electricity and fossil fuel prices in European countries due to the highly integrated power market. As IFE-TIMES-Norway only includes the Norwegian energy system, electricity price projections are given as input by the European power market model, EMPIRE. The prices are developed as part of a bi-directional linkage between EMPIRE and IFE-TIMES-Norway (Haaskjold and Pedrero 2023). In TECH and RAD, electricity prices with adoption of CCS in Europe are assumed. In INC and SOC, CCS does not reach large-scale commercialization in Europe, resulting in higher and more volatile electricity prices.

Hydrogen

Hydrogen can be produced either as grey, blue, or green hydrogen depending on the energy used. Grey hydrogen is not considered a technology for the future, due to the large CO_2 emissions generated during production and hence not included in these analyses. Both blue and green hydrogen are considered as low-carbon solutions which can play an important role to meet net zero emission targets. Blue hydrogen production using Autothermal Reforming (ATR) with CCS does still release some emissions and is dependent on natural gas supply. In the scenarios where the oil and gas sector in Norway is phased-out, blue hydrogen is assumed not to be realized. This includes the SOC and RAD scenarios. Moreover, CCS is limited to the activities of today in INC, preventing blue hydrogen production. Hence, blue hydrogen is only available in TECH.

Green hydrogen is available for all scenarios, but the investment cost differs depending on the expected technology learning rate. For scenarios with *major* technology change (TECH and RAD), a 67-81% reduction in cost is assumed by 2050 depending on the electrolyser type. In comparison, INC and SOC assume only a 53-57% reduction.

Transport

Battery vehicles are highly efficient with low maintenance and fuel costs and are therefore often the preferred solution in a techno-economic optimisation model. To get more realistic results, maximum market shares of selected technologies are added to the model, as seen in Table 5. Conventional technologies such as combustion engines, using both fossil fuels and biofuels, are modelled without limitations.

For heavy-duty applications, the current limited range of battery vehicles is a drawback and can limit their penetration in heavy-duty segments. In a base version of IFE-TIMES-Norway, large trucks driving long distances are not assumed to be battery vehicles, but in the RAD scenario with high electrification and less hydrogen, this limitation is not included, and all these trucks may be battery electric from 2030. On the other hand, in the INC and SOC scenarios, it is assumed that drawbacks in all segments will limit the possible market share of battery vehicles. It is assumed that at least 10% of cars and vans must be other types of vehicles (e.g., combustion engines) and the shares of battery electric trucks and buses are also decreased.

Sea transport is modelled in a simplified way in IFE-TIMES-Norway, as a maximum share of different propulsion alternatives, see Table 5. In the INC and SOC scenarios with less technology development, it is assumed that neither hydrogen nor ammonia will be possible solutions. In the in-depth study of the maritime sector, we are now improving the modelling of the maritime sector by including more details such as more vessel segments.

Air transport and other mobile transport is also modelled with a maximum share of energy carriers. In the INC and SOC scenarios, hydrogen cannot be used, however, in the TECH and RAD scenarios up to 100% of demand for air transport may be hydrogen-based and up to 50% in other transportation. In air transport, the cost of investing in a new fleet is not included.

TABLE 5: MAXIMUM MARKET SHARE OF DIFFERENT TRANSPORT ALTERNATIVES, WITH SCENARIO SPECIFIC SHARES

	Battery		Hydrogen			Ammonia			Gas /LNG		
	2030	2040-	2030	2040-	2050	2025	2030	2040-	2020	2030	2040-
Car			no limits	no limits	no limits	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Van	100%	100%	no limits	no limits	no limits	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Small truck	100%	100%	no limits	no limits	no limits	n.a.	n.a.	n.a.	no limits	no limits	no limits
Large truck, short haulage	100%	100%	no limits	no limits	no limits	n.a.	n.a.	n.a.	no limits	no limits	no limits
Large truck, long haulage	0 %	0 %	no limits	no limits	no limits	n.a.	n.a.	n.a.	no limits	no limits	no limits
Bus	65 %	92 %	no limits	no limits	no limits	n.a.	n.a.	n.a.	5 %	50 %	100 %
Passenger vessels	49 %	49 %	13 %	13 %	13 %	0 %	38 %	38 %	14 %	86 %	86 %
Fishing vessels	5 %	25 %	5 %	25 %	25 %	0 %	5 %	50 %	4 %	25 %	50 %
Other vessels	5 %	10 %	5 %	5 %	5 %	0 %	5 %	90 %	8 %	49 %	90 %
Air	10 %	20 %	0 %	0 %	0 %						
Other mobile transport	37 %	67 %	0 %	0 %	0 %						
	Changes in INC & SOC vs. base										
Car	90 %	90 %	0 %	0 %	0 %						
Van	90 %	90 %	0 %	0 %	0 %						
Small truck	50 %	80 %									
Large truck, short haulage	50 %	80 %									
Bus	50 %	80 %									
Passenger vessels			0 %	0 %	0 %		0 %	0 %			
Fishing vessels			0 %	0 %	0 %		0 %	0 %			
Other vessels			0 %	0 %	0 %		0 %	0 %			
	Changes in RAD vs. base										
Large truck, long haulage	100%	100%									
	Changes in TECH & RAD vs. base										
Air			0%	5 %	100%						
Other transport		80 %		50 %	50 %						

Industry

In the TECH and RAD scenarios, CCS is available for reducing CO_2-emissions in industry sub-sectors as aluminium, other metals, cement, and district heating. In the INC and SOC scenarios, possible use of CCS is limited to the activities of today at the cement plant in Breivik and the district heating plant in Oslo.

In addition to CCS, other possibilities to reduce the CO_2 emissions are included. One possibility is to substitute the use of fossil coal by using bio coal. This is possible in other metals, chemicals, and minerals. Since it is not possible to substitute all fossil coal with bio coal, a limit of maximum 30% in 2030 and 40% in 2040 is applied in other metal production and chemicals, while in mineral industry, an upper limit of 25% is applied. These assumptions are kept the same in all four scenarios.

Some use of coal as raw material in other metals and chemical industry has the possibility to be replaced by hydrogen, with an upper bound of use based on available literature (uncertain data). The use of electrolysis and hydrogen instead of natural gas is a possibility in the chemical industry. Rather mature projects such as Yara and Tizir are assumed to be implemented in all scenarios, while additional possibilities are added to the high-tech scenarios TECH and RAD. Since the industry demand is higher in the TECH scenario than in the RAD scenario, the possible use of hydrogen will also be higher in TECH. All this data and assumptions are uncertain and will be studied further.

Flexibility

In the SOC and RAD scenario, local solutions, and a high degree of behaviour change (e.g., in terms of practices leading to reduced demand, as well as participation in energy conservation) is expected. This is included in IFE-TIMES-Norway as possibilities to move and reduce the energy demand, both in time (peak shaving) and the total use (energy savings). Energy efficiency measures is included as a lower demand of energy services in buildings, as described earlier.

Peak shaving is modelled as a possibility to move in time when electric hot water tanks is heated and when electric cars and vans are charged. For hot water tanks, 30% of the electricity used for heating of water may be moved to a different time of the day, with an additional investment cost (Haaskjold, Rosenberg et al. 2023). A span of flexibility of 50% on *when* EVs are charged (which hour of the day) is applied the SOC scenario and this is further increased to a span of 90% flexibility in the RAD scenario.

In addition, there is a possibility to invest in stationary batteries in all scenarios. In the RAD scenario, a higher technology learning is assumed for the investment costs, see Figure 3. Seasonal storage in district heating plants is possible in all scenarios without any differences in technology data or limitations.

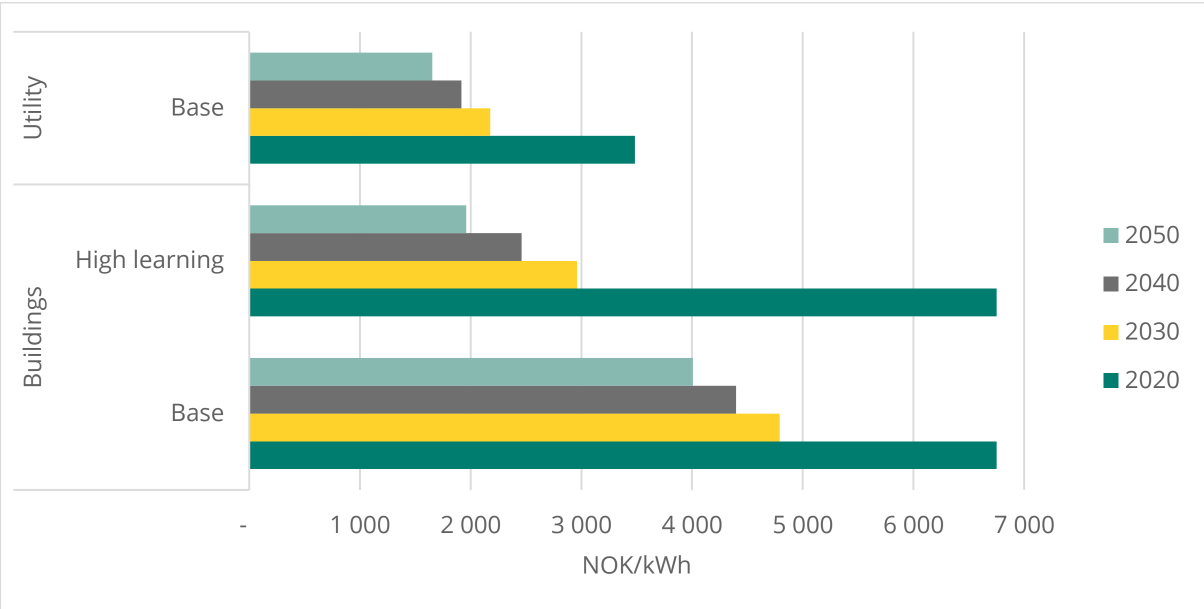

FIGURE 3: INVESTMENT COST OF STATIONARY BATTERIES IN 2020-2050, NOK/KWH

3.1.3 Other quantifications

CO_2

The cost of CO_2 emission is included in IFE-TIMES-Norway as a commodity cost, increasing from 590 NOK/ton CO_2 in 2020 to 2000 NOK/ton CO_2 in 2030, 2960 NOK/ton CO_2 in 2040 and 4382 NOK/ton CO_2 in 2050. The purpose of this in the modelling is to highlight how a low carbon society can be achieved in each of the four scenarios, and it will typically be done by conducting sensitivity analyses of the level of this cost. It can also easily be replaced by a CO_2 cap. In the next steps of the ten-step approach we will include sensitivity analysis to assess uncertainties and bottlenecks in the transition.

Bio energy

Major technological change is understood as how big changes the end-user is exposed to: ICE (internal combustion engines) with biofuels will be a minor change for the end-user, while battery/hydrogen technologies can be regarded as major change for the end-user. Both require major technology changes/development. Replacing large parts of the use of fossil fuels for transportation by biofuels, will require large volumes of bio energy. A scenario assumption is that unlimited bio energy resources for use in combustion engines and as industrial bio coal is available and this assumption is used in the INC and SOC scenarios. Biofuel and bio coal can be traded on an international market with an increase in price as other bio energy products.

In the TECH and RAD scenarios, the assumption that Norway, as a country rich in bio energy resources, must be self-sufficient, is applied as a restriction. The reasoning behind this is that bio energy is a limited resource on the global level and that the global demand will increase as more countries will use it for decarbonization and thus the price will increase and access to biofuel and bio coal will be less available. In IFE-TIMES-Norway it is assumed that mainly Norwegian biomass resources will be used for production of different bio energy products, but, if necessary, it is also possible to use imported biofuel at a high cost (5 times as high as in INC and SOC) in the TECH and RAD scenario.

The use of municipal waste for incineration in district heating plants is assumed to be at the same level as today in the INC and TECH scenarios. In the SOC and RAD scenarios, with a shift towards circular economy, the volume of municipal waste is assumed to be halved compared to today, and it must still be used for incineration in district heating plants.

Hurdle rate

In the SOC and RAD scenario, a high degree of behaviour change and citizen involvement is expected. This is included in IFE-TIMES-Norway as a lower rate for investments in end-use technologies in these scenarios compared to the INC and TECH scenarios. In the SOC and RAD scenario, the hurdle rate is 4%, and in the INC and TECH scenario the rate is 10%. This difference in hurdle rate is applied for all end-use technologies in buildings, transportation, stationary batteries, electrolysers and building applied PV, resulting in a higher cost for these technologies.

3.2 Regional economic modelling

The regional economic modelling is carried out with the CGE model REMES-Norway, a regional model of the Norwegian economy. REMES-Norway is modelled as a Computable General Equilibrium model and is used to analyse the possible responses of the economy to policy decisions or technology innovations. A description of the model and its working principles can be found in the appendix and in (Werner, Perez-Valdes et al. 2017).

3.2.1 Reference scenario

The economic evaluation of the decarbonization scenarios is based on the quantification of the storylines reported at the beginning of the document. Eight main drivers have been considered, namely population growth, productivity, technology improvement, energy intensity, availability of resources, emissions level, shift towards circular economy, and changes in demand of transport. For each of these dimensions an initial set of assumptions have been made to reflect a Business-as-Usual configuration, also known as Reference scenario, which describes the development of the economy if the mentioned drivers maintain nowadays trends. The assumptions used to define the Reference scenario include a 1.9% yearly decrease in oil extraction from 2024, stable gas extraction at 2018 levels, an increase in GDP per person from 2018 to 2050 with a yearly growth of 1.48%, a population growth rate of 0.31% per year, and an increase in power consumption of 0.49% per year. To model the fact that the demand pattern for oil and gas from the rest of the world remains stable until 2050, the weight set on the importance of oil and gas on overall exports is left as calibrated in the base year. This means that if there is an increase in price for one of these resources, their demand from the rest of the world will decrease, given all other conditions. In particular an increase in their price linked to a lower extraction level should lead to a decrease in exports, given all other conditions. The Reference scenario also assumes a 50% decrease in emissions between today and 2050. To achieve this GDP target, the general productivity level has been calibrated to a value ensuring the achievement of the aforementioned GDP level. Similarly, the level of energy intensity has been calibrated to achieve a consumption of energy consistent with the projections from NVE (NVE 2021). More details about the construction of the Reference scenario are reported in Appendix B.

The assumptions defining the Reference scenario are summarized in Table 6. Only the values of the parameters that may be modified under the alternative scenarios are reported.

TABLE 6: MAIN ASSUMPTIONS USED TO MODEL THE REFERENCE SCENARIO

Reference scenario	
Aspect	**Quantification**
Population	0.31 % yearly
Productivity	Calibrated to be consistent with the official projections for GDP growth (Long-term Perspectives on the Norwegian Economy 2021)
Technology	Endogenous
Energy intensity	Calibrated to be consistent with the official projections for energy consumption (NVE)
Deployment of resources	1.9% yearly decrease extraction for oil Stable natural gas extraction
Export of resources	Constant weight for oil and gas in the export function at 2018 level
Circular Economy	-
CO2 emission cap decrease towards 2050	50 % compared to 2018
Transport	-

3.2.2 Socio-technical scenarios

The quantification of the four socio-technical scenarios is based on the modification of the parameters considered in Table 6 or including additional shocks. More specifically, the quantification process for the NTRANS scenarios starts by defining eight main aspects characterizing the development of the economy: population, productivity, technology, energy intensity, deployment of resources, export of resources, shift toward circular economy and transport development. To describe the alternative scenarios, each of the relevant aforementioned aspects are mapped to one or more sentences used in the storyline and then assigned to one or more parameters. Thus, based on the storyline claims, additional assumptions in line with the pathway narrative have been formulated for these parameters. As a mention, the differences between the focus on growth and on well-being have been modelled by decreasing the total factor productivity by 1% per year compared to the Reference scenario in case of focus on well-being; this is done to simulate a society in which working time is decreased to leave more space for leisure time. Oil and gas extraction tend to decrease in every scenario with different intensities, while their export demand might remain constant to 2018 levels to reflect that many countries will reduce the usage of oil and gas, but others may not, or decrease, depending on the considered scenario. In particular, under SOC and RAD scenarios the extractions of oil and gas approach zero around 2040, based on the projections of the activity level of these sectors. The phase out of the oil and gas extractions in REMES happen slightly later compared to what is projected by IFE-TIMES-Norway, which sets the complete elimination of oil and gas extractions by 2034. This has led to a tabular scheme representation for each of the storylines. The change in transportation habits has been modelled by changing the structure of the utility function defining the purchase preferences of the households. This function assigns different weights to different commodities to specify how much such commodities are important in the consumption pattern of the households. The transition towards a society relying less on private transportation has been modelled shifting the purchase of fuels towards the purchase of collective transport. This has been accomplished by reducing the weight placed on the purchase of fuels in the utility function and increasing the weight for the usage of public transport. A similar approach is used to model the change in preferences from manufactured goods to services so to implement the transition towards a circular economy paradigm. Also, the same approach has been used to model the decrease in demand of oil and gas from the rest of the world. Namely, the weight assigned to oil and gas in the export function has been gradually reduced towards 2050 under the Social Change and Technological Change scenarios. This has led to a decrease in demand for these resources from the rest of the world independent on the change in prices and has been modelled to reflect the fact that these resources will not be used any longer (at least at the scale in which they are used today) by the rest of the world. For what concerns the technological aspects, the quantification of the energy mix employed in the different sectors is always claimed as "external"; this means that the energy mix considered for each sector and for the final demand is considered as an input taken from the results of the IFE-TIMES-Norway energy system model; moreover, if hydrogen is not considered, the relevant hydrogen sectors are locked as inactive in REMES-Norway. Some differences arise between the assumptions related to CCS used in industry between REMES-Norway and IFE-TIMES-Norway. In the energy system model, the use of CCS is limited, while in the economic model CCS is included in the whole macro-sector. The details on how the energy mix projections from IFE-TIMES-Norway are included in REMES-Norway are explained in the following sub-chapter.

The details of the implementation of the NTRANS scenarios are described in the following tables.

TABLE 7: MAIN ASSUMPTIONS USED TO MODEL THE INCREMENTAL INNOVATION SCENARIO

Incremental Innovation		
Aspect	**Storyline claim**	**Quantification**
Population	Steady increase	0.31% yearly
Productivity	Focus on growth	As in Reference
Technology	-	External - No H2 - CCS in industry
Energy intensity	**-**	As in Reference
Deployment of resources	Still global oil and gas	1.9% yearly decrease extraction for oil Stable natural gas extraction at 2018 level
Export of resources	Still global oil and gas	Constant weight for oil and gas in the export function at 2018 level
Circular Economy	-	As in Reference
Transport	Increasing demand	As in Reference

TABLE 8: MAIN ASSUMPTIONS USED TO MODEL THE TECHNOLOGICAL CHANGE SCENARIO

Technological Change		
Aspect	**Storyline claim**	**Quantification**
Population	Steady increase	0.31% yearly
Productivity	Focus on growth	As in Reference
Technology	CCS (for hard-to-abate sectors) developing fast	External with H2 – CCS in industry
Energy intensity	-	As in Reference
Deployment of resources	some oil and gas	10% yearly decrease extraction for oil Stable natural gas extraction to 2018 level
Export of resources	some oil and gas	Phase-out (Gradual decrease in the weight for oil and gas in the export function)
Circular Economy	-	As in Reference
Transport	Increasing demand	As in Reference

TABLE 9: MAIN ASSUMPTIONS USED TO MODEL THE SOCIAL CHANGE SCENARIO

Social Change		
Aspect	**Storyline claim**	**Quantification**
Population	Halting	0 % yearly
Productivity	Focus on well-being	1% yearly decrease in labour productivity
Technology	-	External
Energy intensity	Energy-efficiency	10% lower energy intensity than reference in 2050
Deployment of resources	Limited oil and gas	25% yearly decrease extraction for oil 25% yearly decrease extraction for natural gas
Export of resources	Limited oil and gas	Phase-out (Gradual decrease in the weight for oil and gas in the export function)
Circular Economy	Circular economy	Adjustment of the relative importance of manufactory and services in the utility and production functions. 10% decrease in weight for preference on products in the input function rebalanced towards services
Transport	Less transport needs	Adjustment of the relative importance of fuel purchases in the preferences of households towards the use of public transport. 10% decrease in weight for preference on fuels and 10% increase in weight of transport in the utility function of households

TABLE 10: MAIN ASSUMPTIONS USED TO MODEL THE RADICAL TRANSFORMATIVE SCENARIO

Radical Transformative		
Aspect	**Storyline claim**	**Quantification**
Population	Halting	0% yearly
Productivity	Focus on well-being Industry 5.0	1% yearly decrease in labour productivity 1% yearly increase in Total Factor Productivity for industry
Technology	Renewable H2	External - H2 from electrolysis – CCS in industry
Energy intensity	Energy-efficiency	30% lower energy intensity than Reference in 2050
Deployment of resources	Some oil and gas	25% yearly decrease extraction for oil 25% yearly decrease extraction for natural gas
Export of resources	Some oil and gas	Phase out
Circular Economy	Circular economy	Adjustment of the relative importance of manufactory and services in the utility and production functions. 10% decrease in weight for preference on products in the input function rebalanced towards services
Transport	Reduced demand for transport	Adjustment of the relative importance of transport and services in the utility and production functions. 10% decrease in weight for preference on transport in the input function rebalanced towards services

Under every alternative scenario the assumption for GHG emissions is a decrease of 90% towards 2050 compared to the base year (2018).

3.2.3 Modelling procedure

In the summary boxes, technology has been often defined as "external". This means that the projections of the energy mix in the economy towards 2050 are included in REMES-Norway as input data. This data is obtained by the output of the IFE-TIMES-Norway model in energy units (GWh/year). Nevertheless, the dataset used in the REMES-Norway model is measured in Million Euro per year. This means that a harmonization process is needed to make the data as compatible as possible.

The harmonization is based on splitting the REMES-Norway dataset into a price index and a quantity index. The quantity index is used to mimic the behaviour of the energy mix shares in order to be coherent with their behaviour as projected by the IFE-TIMES-Norway model, while the price index is used to reconcile the initial values for the energy mix to the ones found in the REMES-Norway initial data.

The harmonization steps are as follows:

1. Allocate the values obtained from IFE-TIMES-Norway into all the regions and sectors mapped to the considered IFE-TIMES-Norway sector. Even if IFE-TIMES-Norway has a high granularity in the definition of industrial subsectors, for this modelling exercise, and to avoid problems on the different definition of industrial sectors in the two models, the information has been passed to REMES-Norway in an aggregated manner using a single "industry" sector. In REMES-

Norway this needs to be allocated into the various industries that are modelled and located into the 5 macro-regions considered in the model.

2. Create a quantity index by multiplying the total value of the overall energy consumption in a sector from REMES by the share of demand of a given commodity in the same sector taken from the TIMES data (allocated proportionally into REMES).
    a. The result will not be the original consumption in the REMES data, as the used shares are from TIMES and are applied to the total consumption of energy commodities from REMES.
3. To harmonize this quantity index with the initial value in REMES one needs to create a suitable (price) multiplier. To obtain such a multiplier, we compute the ratio between the consumption of the considered commodity in each sector in the REMES data and the value obtained with the TIMES data allocated as for point 1.
4. When this price index is multiplied by the quantity index from point 2, it gives back the initial consumption of the aforementioned commodity in REMES; nevertheless, this value will develop over time following the pattern provided by the TIMES data.
5. The average value of the prices that are computed for the commodities are used to create an initial price to assign to any commodity that was not featured in the REMES dataset in the base year, such as hydrogen.
6. Multiplying such prices (from 3.) by the quantity (from 2.) will supply values that, once normalized to unit per sector, will provide shares that can be used in REMES as multipliers for the initial data in the Social Accounting Matrix to reflect the behaviour of the output in the IFE-TIMES-Norway model.

This procedure works well as long as the datasets do not present remarkably different initial datasets. This means that if there are commodities featured in the IFE-TIMES-Norway that are not in REMES-Norway in the base year, the model might not be able to reflect the behaviour of the IFE-TIMES-Norway output properly. This also happens if the REMES-Norway initial data features commodities in the energy mix of a given sector that are not featured in the IFE-TIMES-Norway data in the base year. Finally, if the two models start with a similar allocation of energy commodities across sectors, meaning they use the same percentage of each commodity in each sector, then the development of technology over time will be more consistent and aligned between the two models.

4. Scenario results

4.1 Techno-economic analyses

This chapter describes the results from analyses made with the energy system model IFE-TIMES-Norway with the scenario assumptions described in the paragraph "3.1 Techno-economic modelling".

4.1.1 Power generation

Figure 4 shows the model results of the electricity generation mix in Norway for each scenario from 2020 to 2050. In scenarios with low energy service demand, the increase in energy production is limited with additional 30 and 38 TWh by 2050 in SOC and RAD, respectively. New production is mainly supplied by building applied PV (BAPV), with only reinvestments in existing wind capacity. Of the total generation mix, hydropower constitutes 81% and increase by 9-15 TWh compared to the production in 2020. In INC and TECH, onshore wind reaches its upper production potential with 48 TWh by 2050, while the adoption of BAPV is minor due to the higher hurdle rate. The TECH scenario stands out with more than a doubling in energy generation from 2020, reaching 380 TWh by 2050. Offshore wind is the main supplier with 164 TWh, corresponding to 43% of the total generation. Hence, the offshore wind share exceeds that of hydropower (41%).

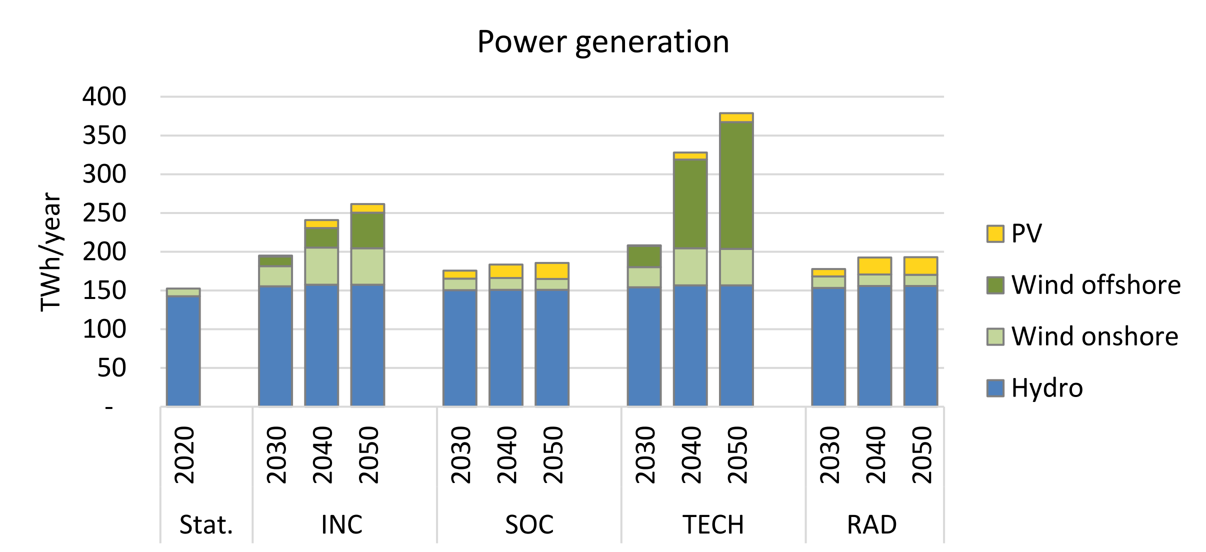

FIGURE 4: POWER GENERATION BY TECHNOLOGY AND SCENARIO FROM 2020 TO 2050 (TWH/YEAR)

As with the power production, the electricity use also varies between the four scenarios, see Figure 5. For all scenarios, the electricity use in buildings decline because of increased use of district heat and bio energy boilers in combination with more efficient heat pumps and less direct electric heating and electric boilers. The energy service demand in SOC and RAD is decreasing due to the assumption that 15 TWh of energy efficiency measures are implemented. The main differences between the scenarios relate to the electricity use in industry. The major increase in industry activity assumed in the TECH scenario result in 70 TWh additional electricity consumption by 2050 relative to 2020. In comparison, INC has an increase of 40 TWh, while SOC and RAD have a minor decrease of 2 TWh, mainly due to the phase-out of the O&G industry. Lastly, large volumes of green hydrogen production occur in the TECH and RAD scenario, as a result of high technology development and learning.

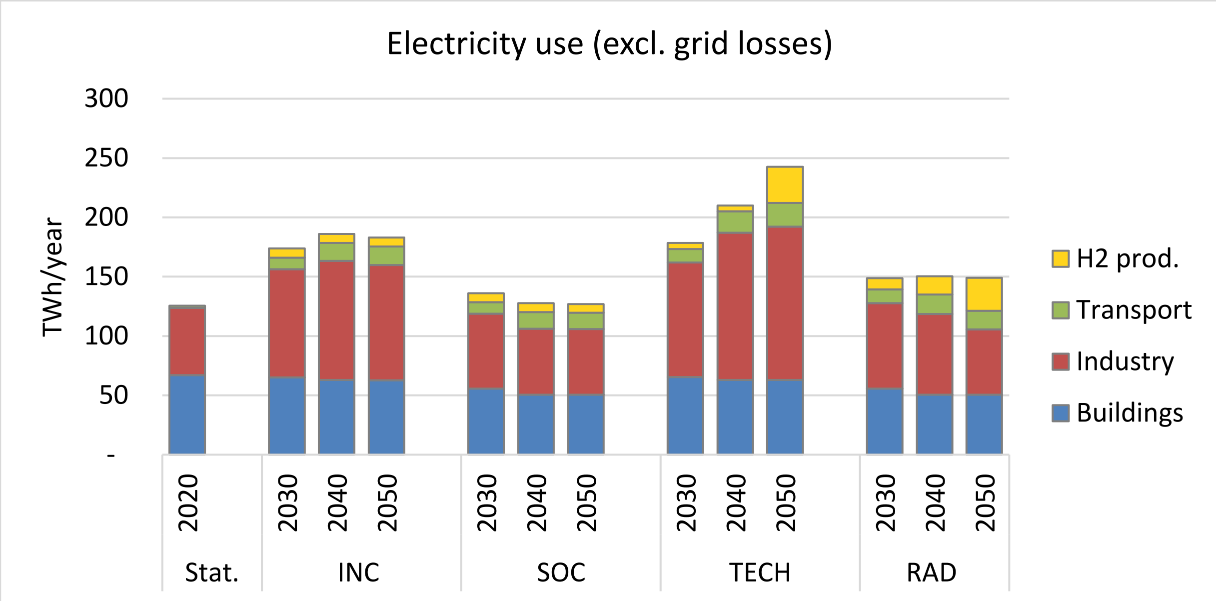

FIGURE 5: ELECTRICITY USE BY SECTOR AND SCENARIO FROM 2020 TO 2050 (TWH/YEAR)

The net power export to Europe is largely correlated to the domestic energy service demand and power generation, as illustrated in Figure 4 and Figure 5. The INC and TECH scenario have high power generation to enable large export volumes. Moreover, the traded volumes are dependent on the restrictions enforced on the expansion of new transmission cables to Europe. In SOC and RAD, no new transmission cables are allowed. Hence, even though energy demand is low, the net export volumes are restricted to that of today's transmission capacity. Lastly, the trading of offshore wind capacity significantly impacts the overall net values. While SOC and RAD only allow for radial connections to Norway, INC and TECH can gain from hybrid cables, making offshore wind a more profitable solution. This can also be observed from the power generation mix in Figure 4, where no investments occur in offshore wind for the scenarios with radial connections.

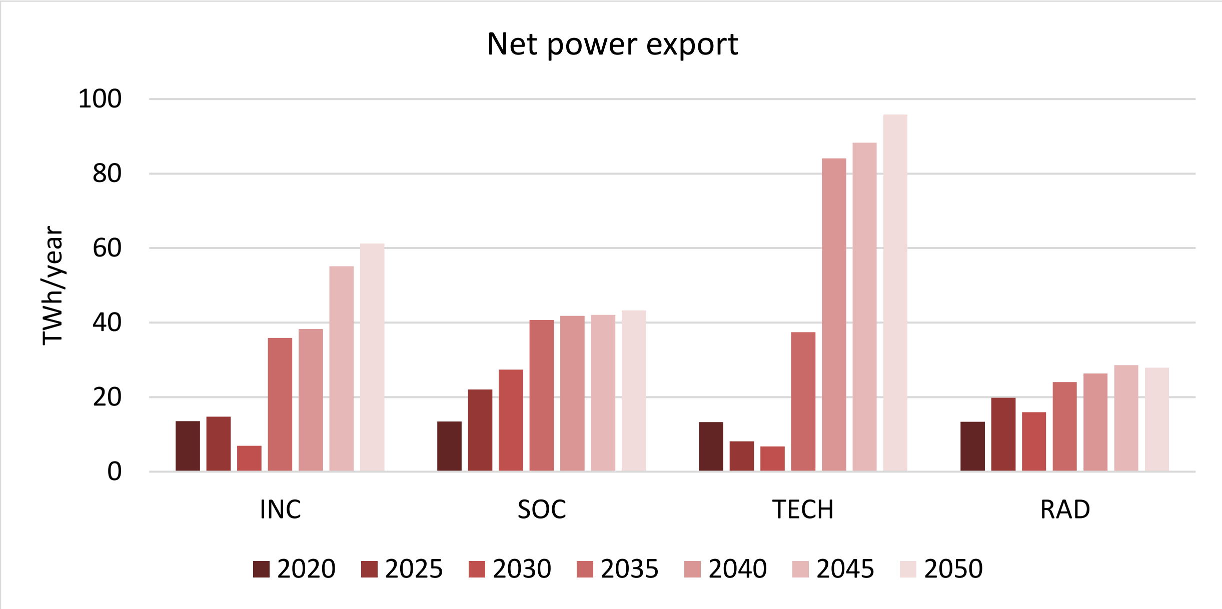

FIGURE 6: NET POWER EXPORT TO EUROPE BY SCENARIO AND PERIOD (TWH/YEAR)

4.1.2 Energy use

The final energy use is reduced in all scenarios, except TECH, due to the high increase in demand in this scenario, as seen in Figure 7. The energy use for transportation is reduced in all scenarios, since the efficiency is greatly improved by extensive use of battery electric transport replacing more inefficient internal combustion engines. The energy use in buildings is constant in the INC and TECH scenarios, 80 TWh/year, and decrease by 19 TWh in the SOC and RAD scenarios.

The largest differences are observed in industry, due to different demand projections, including the development of oil and gas extraction. The SOC and RAD scenarios have no oil and gas extraction after 2035, almost no new industrial plants and constant energy service demand in the rest of the industry, resulting in a final energy use of 102 TWh/year in SOC and 112 TWh/year in RAD in 2050. The INC scenario assumes a small increase in traditional industry, new industry activities with a demand of 20 TWh/year and a decrease in oil and gas extraction to 1/3 of today's level. All in all, this results in a decreased energy use by 30 TWh in 2050 compared to 2020. In the TECH scenario, energy use in industry increase to 295 TWh/year in 2050, an increase by almost 120 TWh/year in 2050 compared to 2020. For this scenario, the oil and gas extraction are reduced to about one-third of today's level, but production of blue hydrogen for export is included.

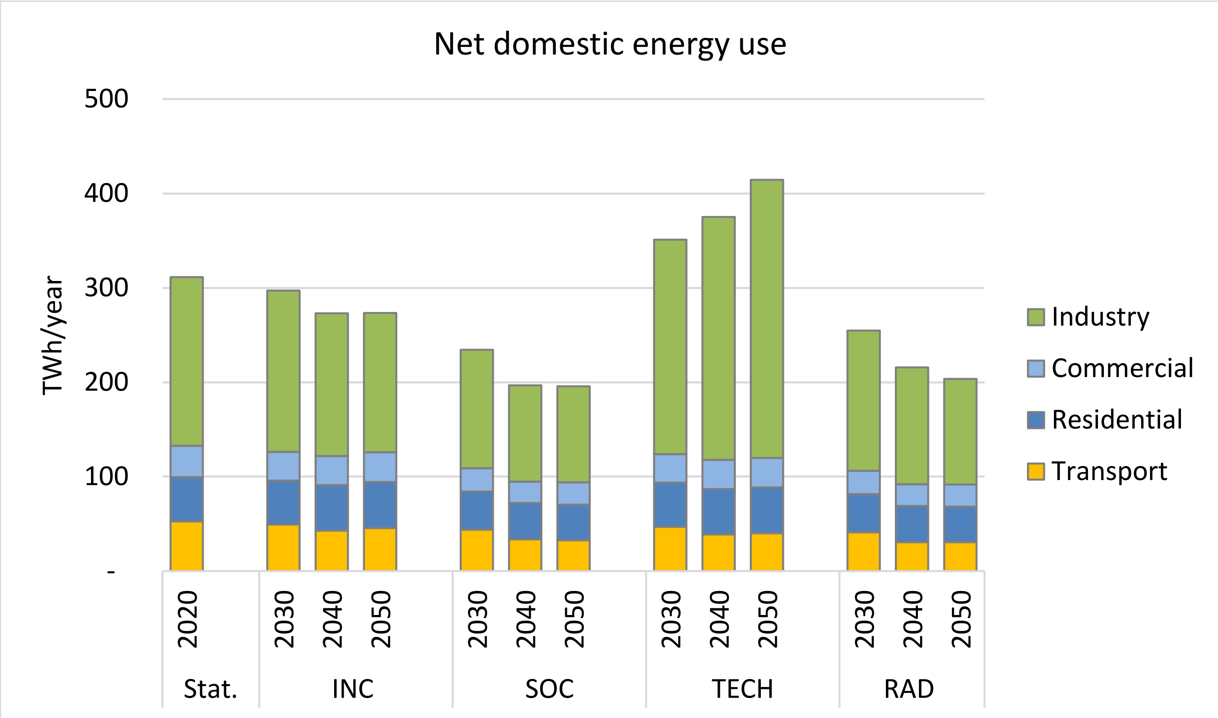

FIGURE 7: USE OF ENERGY IN INDUSTRY, COMMERCIAL AND RESIDENTIAL BUILDINGS AND IN TRANSPORT (TWH/YEAR)

The energy use by energy carrier is presented in Figure 8. The main energy carrier is electricity, and it is increasing in all scenarios, from 10 TWh/year increase in SOC to almost 100 TWh/year in TECH, in 2050. The use of bio energy also increases in all scenarios, and the most is used in the INC scenario (see more details below). Natural gas is used for production of blue hydrogen for export in TECH and this increases the total use of energy by 150 TWh in 2050. Some fossil fuels remain in 2050, due to lack of opportunities in some cases and partly due to the high cost compared to the CO_2 price used in these analyses.

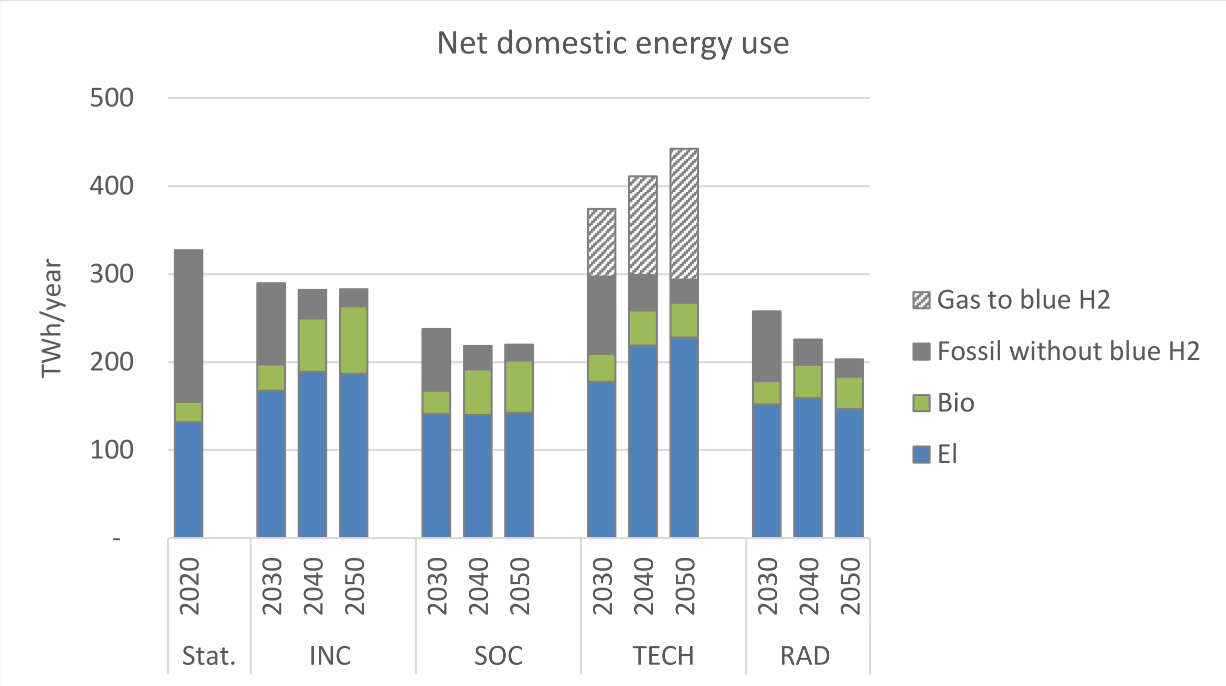

FIGURE 8: FINAL ENERGY USE BY ENERGY CARRIER (TWH/YEAR)

While INC and SOC only have hydrogen use in industry, the energy carrier is widely used in the transport sector in TECH and RAD. Sea transport has the highest share, followed by trucks (in TECH), air transport and other transport. Moreover, hydrogen is used to its upper limit for the chemical industry processes in the TECH and RAD scenarios.

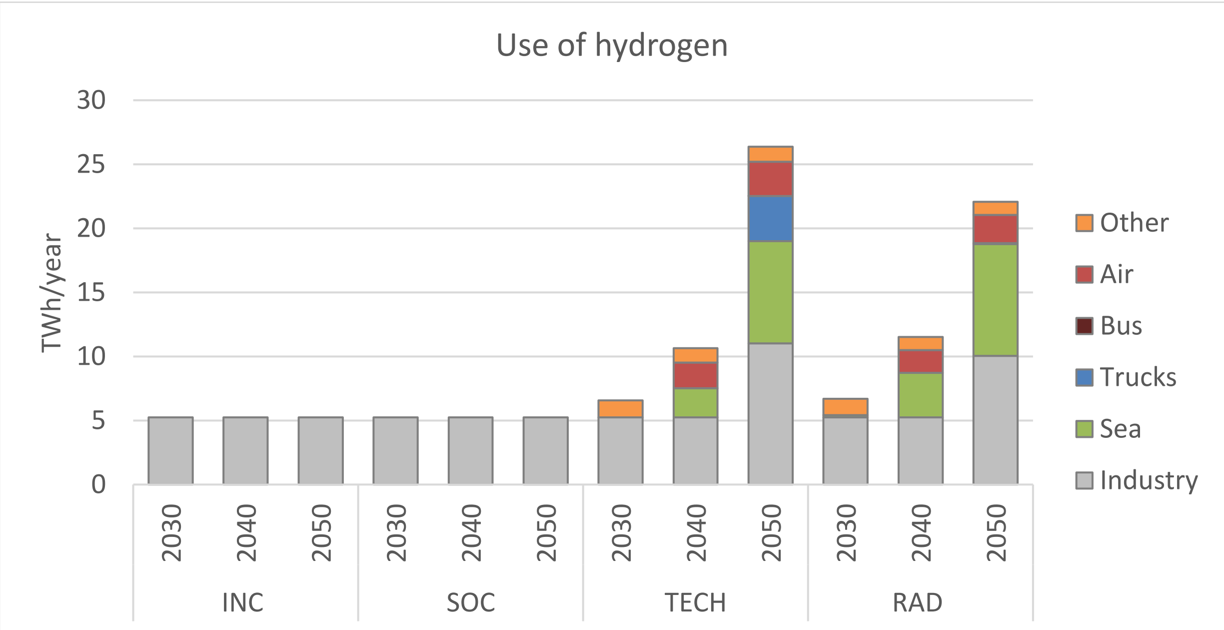

FIGURE 9: USE OF HYDROGEN BY SECTOR (TWH/YEAR)

All domestic biomass resources are used in the four scenarios in 2050, see Figure 10. Import of biofuel or bio coal is expensive in the TECH and RAD scenarios and therefore not used. In the INC and SOC scenarios, where it is possible to import bio at a low cost, a total of 30 TWh biofuels and 7.1 TWh bio coal is imported in INC and 19 TWh biofuel and 3.8 TWh bio coal in SOC. Domestic biomass resources are used to produce bio coal in all scenarios; 17 TWh in SOC, 13 TWh in RAD, 11 TWh in INC and only 6 TWh in TECH, due to less available resources. Biofuel is produced from domestic resources in RAD and TECH, 3.9 and 5.4 TWh, respectively. A large share of biomass is used as raw material in industry in all scenarios (36-42%) and for heating in buildings (incl. use in district heating plants; 10-22%).

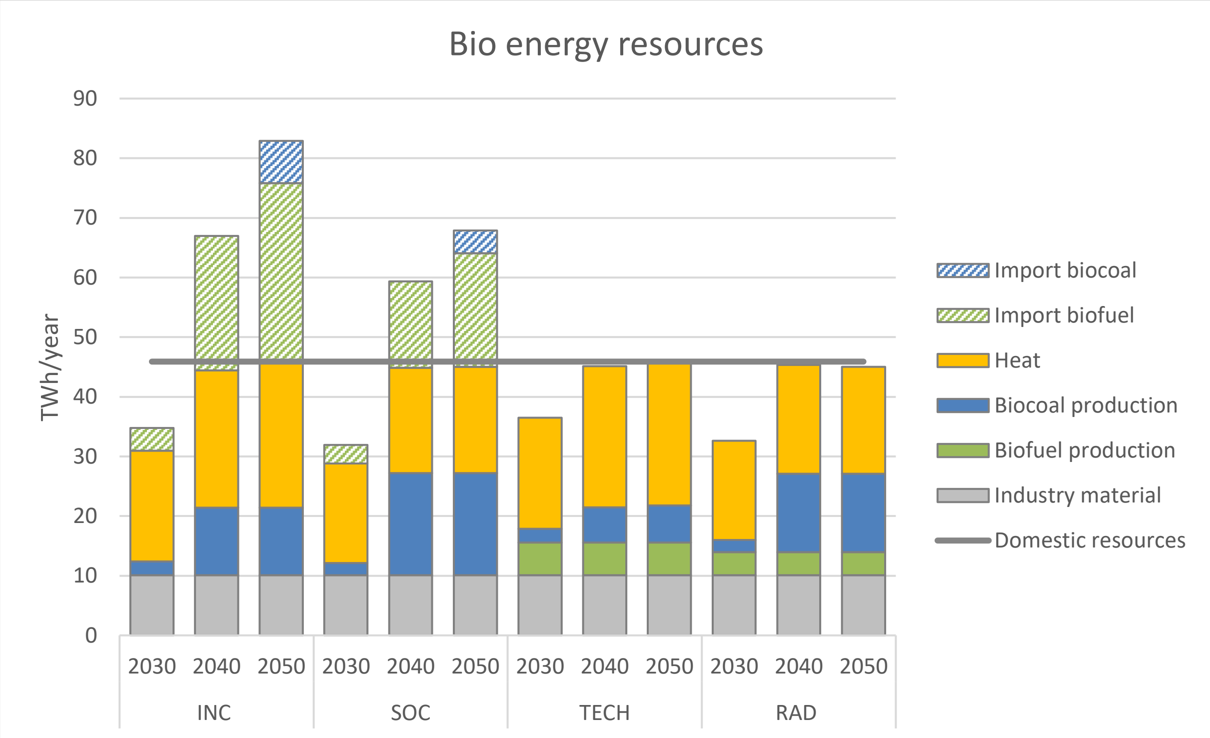

FIGURE 10: USE OF BIO ENERGY RESOURCES FOR PRODUCTION OF BIOFUEL, BIO COAL AND IN BIO BOILERS AND STOVES, AS WELL AS IMPORT OF BIOFUEL AND BIO COAL AND TOTAL DOMESTIC RESOURCES OF SOLID BIO ENERGY (TWH/YEAR)

The use of biofuel per transport mode is presented in Figure 11. The largest use of biofuel is by trucks in the INC scenario, 12 TWh in 2050. Sea transport use about 7-9 TWh in 2040-2050 in both the INC and the SOC scenarios. Also, air transport has a high use of biofuel in these scenarios, about 4 TWh in 2050.

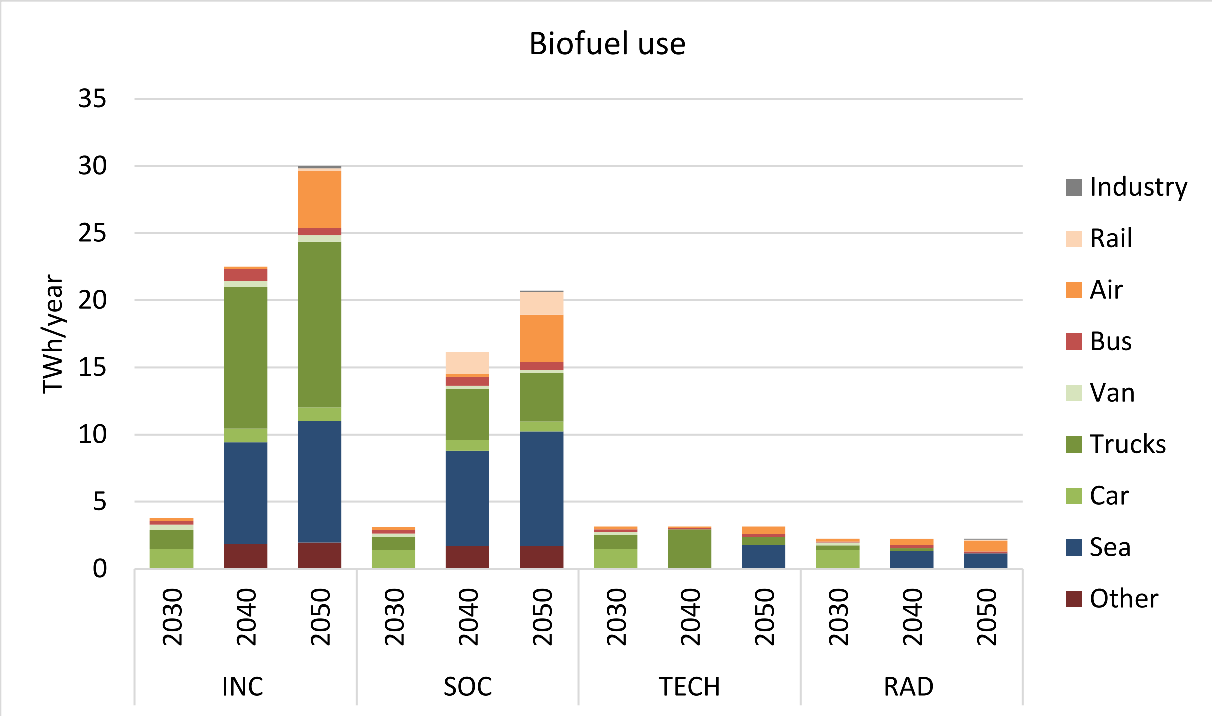

FIGURE 11: USE OF BIOFUEL PER TRANSPORT MODE (TWH/YEAR)

The transport sector is largely decarbonized by 2050 for all scenarios, see Figure 12. In the INC and SOC scenario, where biomass is unlimited and biofuel is cheap to import, the energy consumption from the transport sector is fully supplied by bioproducts and electricity by 2050. In the TECH and RAD scenario where high technology learning is present, hydrogen occur as a profitable fuel for the transport sector, while biofuel is less dominant. Hydrogen is mainly used in trucks, sea (ammonia and direct hydrogen use), and air transport. Due to higher prices on biofuel import in the two latter scenarios, the air transport is still using a small amount of fossil fuel in 2050.

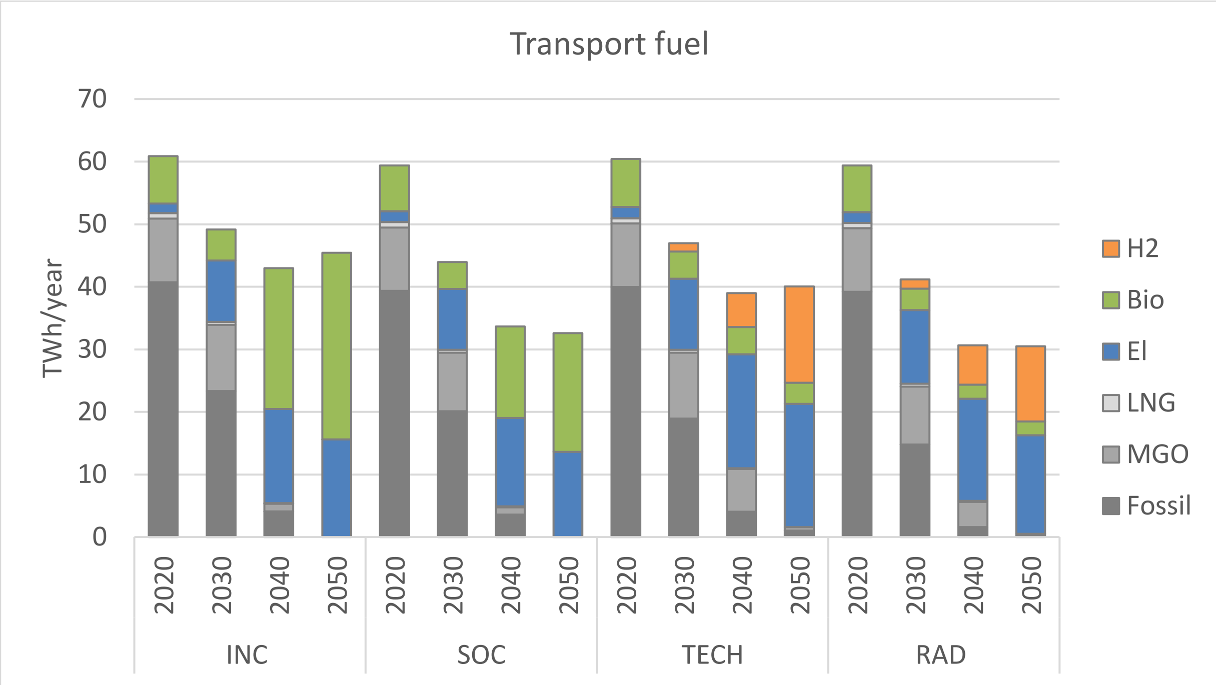

FIGURE 12: ENERGY USE IN THE TRANSPORT SECTOR (TWH/YEAR)

In terms of road transport, electricity is the dominating fuel for all scenarios except INC, where biofuel is largely present (see Figure 13). The use of biofuel is mainly for trucks, with a smaller share in cars and buses. Battery electric vehicles is used, when possible, due to the high efficiency and technology learning. The market share of battery electric vehicle is limited in INC and SOC (see Table 5), resulting in more use of ICE vehicles with biofuels.

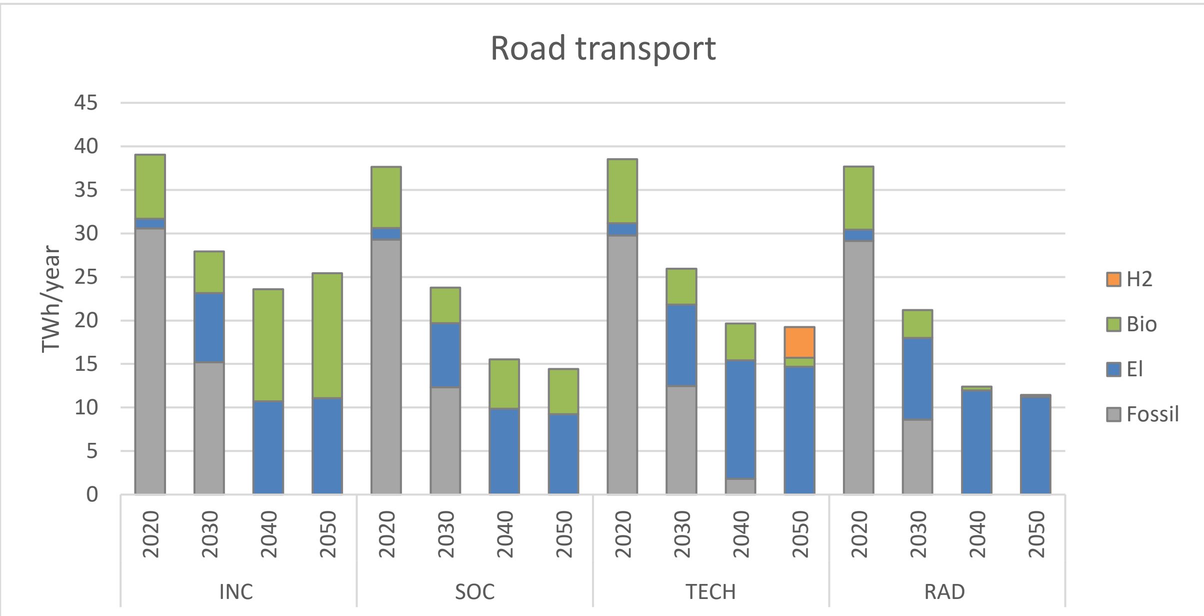

FIGURE 13: ENERGY USE IN ROAD TRANSPORT (TWH/YEAR)

In sea transport, marine gas oil (MGO) and liquified natural gas (LNG) are phased out in all scenarios except for a small share in the TECH scenario, as seen in Figure 14. Electricity constitutes about 16% of total energy consumption in sea transport for all scenarios. While the INC and SOC scenarios are dominated by biofuel, ammonia supplies most of the sea transport in the TECH and RAD scenarios. This is related to the assumed market share of ammonia in the maritime sector, where a higher share is assumed compared to hydrogen (see Table 5). However, hydrogen has a higher overall efficiency compared to ammonia and is thus used when possible.

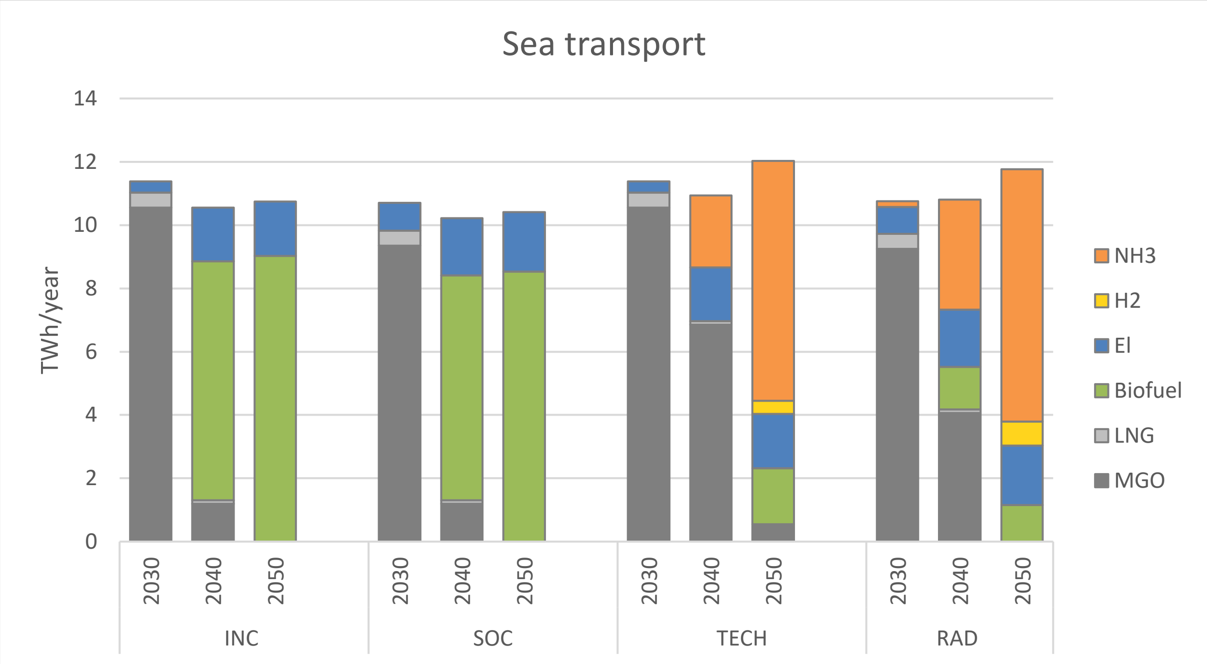

FIGURE 14: ENERGY USE IN SEA TRANSPORT (TWH/YEAR)

4.1.3 CO2 emissions

The CO_2 emissions are reduced by 87-96 % in 2050 compared to the emissions included in the model in 2018, see Figure 15. The industry has the highest emissions in 2050 in all scenarios as the model doesn't include possibilities to fully decarbonize the industry. For TECH and RAD, where additional options for use of CCS are included, the emissions from industry are decreased more than in the INC and SOC scenarios with less potential for industrial CCS. The TECH and RAD scenarios also allow for more use of hydrogen as a replacement for fossil raw materials, further reducing the CO_2 emissions from industry in these scenarios. The cost of using bio coal is lower in the INC and SOC scenarios and hence bio coal is used to a larger extent to reduce fossil CO_2 emissions compared to TECH and RAD.

District heating plants must use municipal waste, and some emissions remain even if CCS is used by all plants in the TECH and RAD scenarios. In the INC and SOC scenarios, CCS is restricted to only one district heating plant.

The CO_2 emissions in transportation are zero in the INC and SOC scenarios, where no limitations on use of bio energy products at a reasonable cost exist. The possible use of bio energy products in the TECH and RAD scenarios is very expensive, and the CO_2 cost applied in the scenarios is not sufficient to make it profitable to import bio energy. Hence, when the domestic bio energy resources are used, some fossil energy is supplemented in these scenarios. The reduced end-use demand in the RAD scenario makes it possible to use bio energy in most cases where electricity or hydrogen is not possible, and the only remaining use of fossil fuel is in some aviation. The TECH scenario has a much higher energy demand, and the available domestic bio energy is far from sufficient. Hence, fossil fuels are used in both aviation and in other sea freight vessels.

The production of blue hydrogen for export also has CO_2 emissions after capturing 95% of the CO_2 emissions, and in the TECH scenarios this gives 1.8 mill. tons of CO_2 emissions in 2050, with the assumed export of 100 TWh.

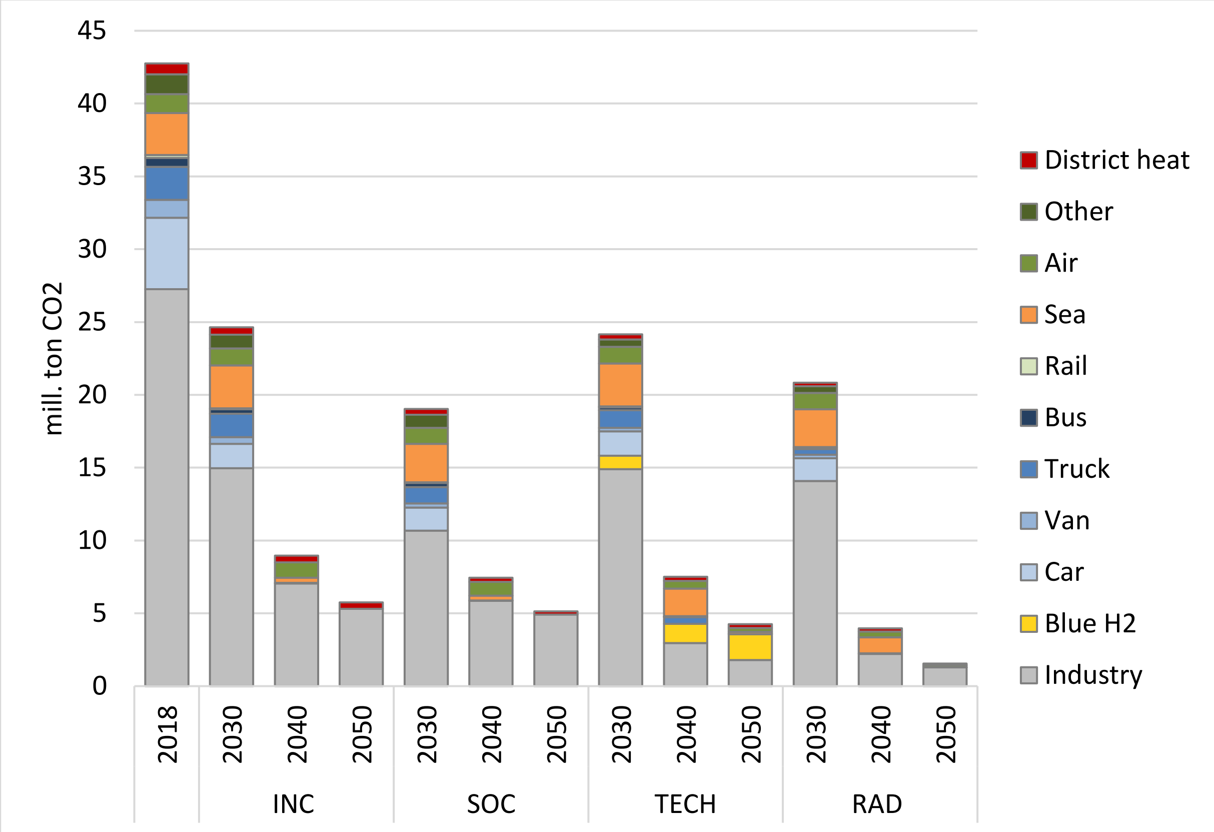

FIGURE 15: CO2 EMISSIONS BY END-USE AND SCENARIO (MILLION TONS OF CO2/YEAR)

4.2 Regional economic analyses

4.2.1 GDP and value added

The typical economic growth pattern of the decarbonization scenarios considers an initial reduction in GDP growth due to the decrease in value added for the oil and gas sectors, followed by a gradual improvement of the growth reached thanks to the larger availability of capitals leading to large investments in industry and services. As shown in Figure 16, the Incremental Innovation Pathway (INC) displays a similar development, that is only relatively smaller than the one for the Reference scenario. This is due to the similarities that this scenario shares with the Reference, most notably the continued exploitation of oil and gas fields. The economic growth for this scenario shows a reduction compared to the Reference scenario towards 2050, when the requirements for decarbonization become more stringent and sectors incur in higher costs - mostly related to the high price of GHG allowances - in order to drastically reduce their emissions.

The TECH scenario is characterized by a more pronounced decrease in oil and gas exports, which are entirely ceased by 2050 with the extraction of oil decreases by around 90% Domestically, gas is subject to an increase in usage in chemicals and in the production of blue hydrogen. This faster phase out compared to the reference scenario and the INC scenario leads to a greater decrease in GDP in the short run. Thanks to the widespread adoption of hydrogen and the implementation of CCS in industry, along with the reduced capital costs resulting from divestment in the oil and gas sector, the scenario demonstrates an increase in value added across most sectors. This allows the GDP growth to almost align to the one displayed by the INC scenario.

On the other hand, the different economic focus, based on societal change, characterizing the Social Change Pathway (SOC) and the Radical Transformation Pathway (RAD), imply a reduced capacity of these scenarios to turn the tides on growth and reach a GDP level comparable to the one reached under the Reference scenario. This has been modelled assuming the development of a legislation framework allowing workers more free time, which will reduce the overall productivity (even if the hourly productivity might rise). The weaker growth displayed by these two scenarios is mostly due to the lower labour productivity and the strong phase-out of oil and gas extractions. Productivity loss under the RAD scenario is slightly mildened by the counteracting effect of the increase in industrial productivity (the so-called Industry 5.0 factor) and the usage of CCS in industry. The results are similar under a per-capita viewpoint, shown in Figure 17.

Figure 18 shows the development of the GDP under the different scenarios decomposed into its main value-added components. Here it is possible to notice that, under the INC and TECH scenario, industry experiences a growth slightly weaker than the one in the Reference scenario. For what concerns services, the INC scenario, has a relatively weaker value-added development compared to the Reference, while the TECH scenario shows a very strong increase in value added for services. If we couple these different developments for the services sector value added and the different developments of the oil and gas sector it is easy to notice that the overall growth under these two scenarios is only slightly weaker than the growth characterizing the Reference scenario. Namely, even if the value growth in the service sector does not manage to completely offset the decrease in value from the oil and gas sector, it manages to cover a large part of this loss. As mentioned earlier, for the SOC and RAD scenarios, the growth for both industry and services are much weaker compared to the previous two scenarios, each scenario for different reasons. The RAD scenario has a decrease in labour productivity, coupled with a halting in population growth, but with the counterbalancing effect of an increase in industrial productivity and the exploitment of technological innovations in CCS and hydrogen, while the SOC scenario has only a decrease in productivity to reduce the growth, but no counterbalancing feature.

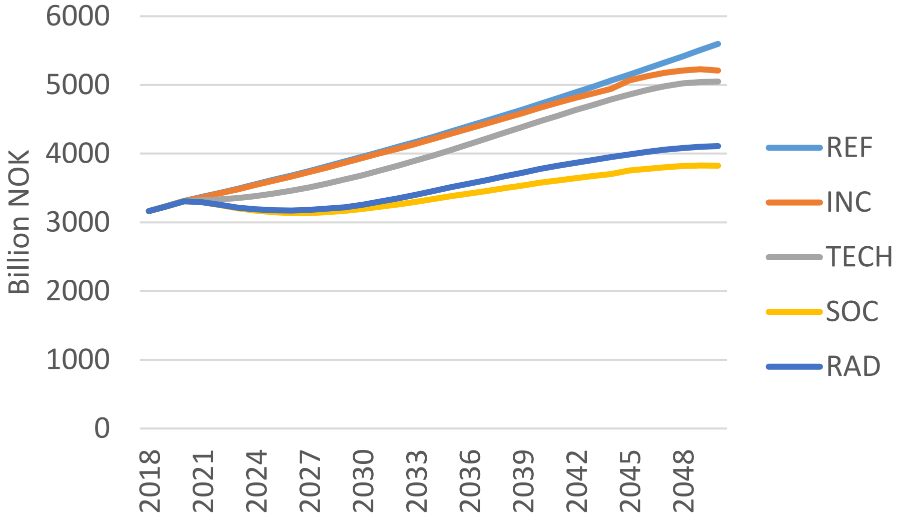

FIGURE 16: GDP DEVELOPMENT TOWARDS 2050 UNDER THE REFERENCE SCENARIO AND THE ALTERNATIVE SCENARIOS

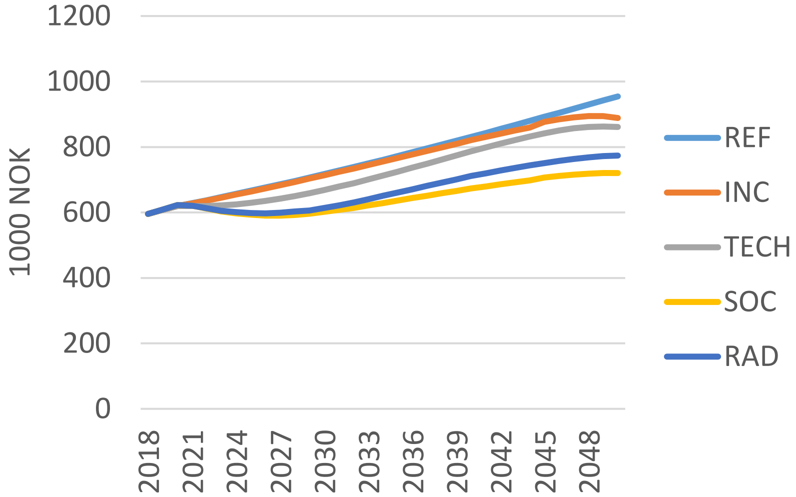

FIGURE 17: DEVELOPMENT OF GDP PER CAPITA UNDER THE REFERENCE SCENARIO AND THE ALTERNATIVE SCENARIOS

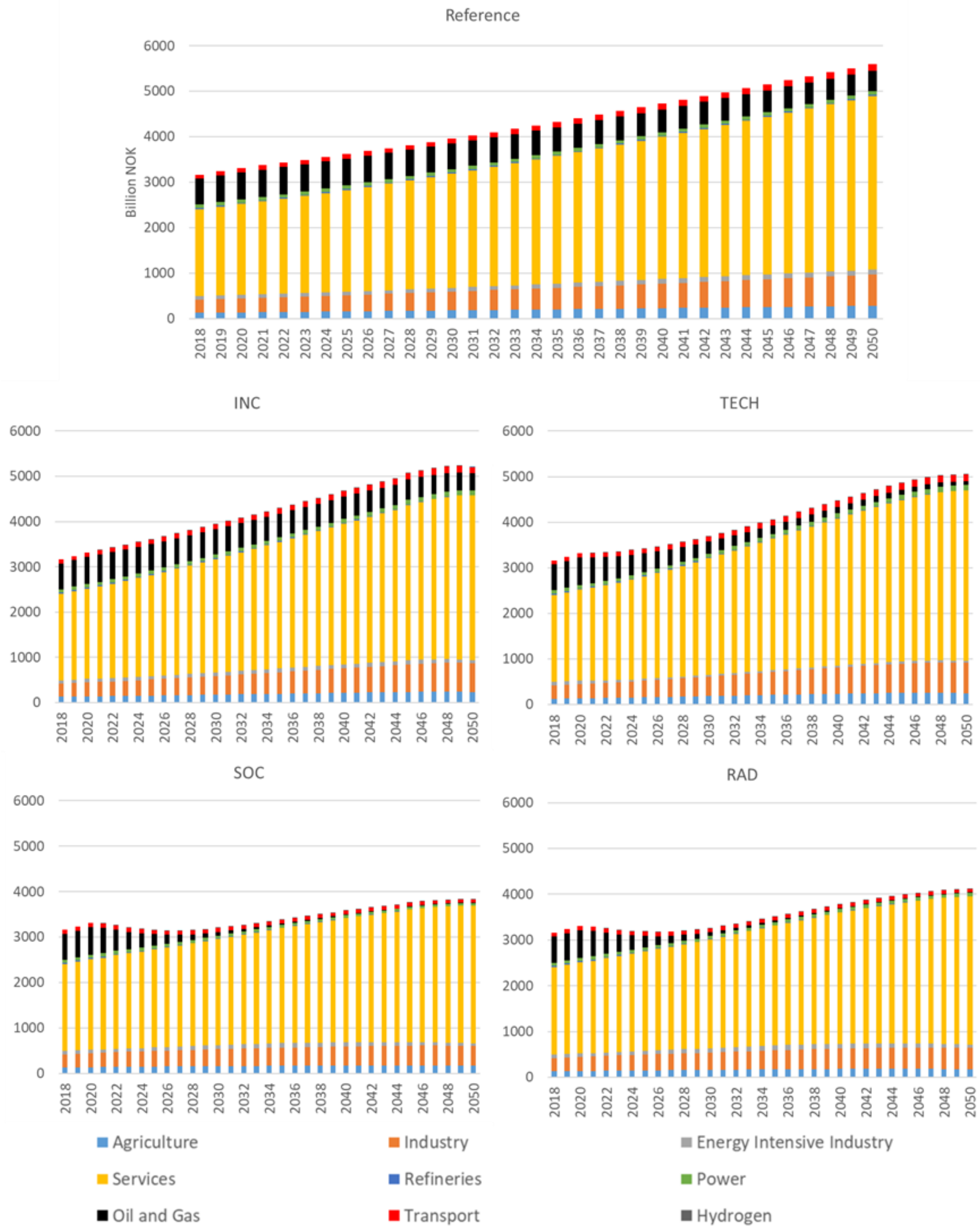

FIGURE 18: VALUE ADDED DISAGGREGATION OF GDP GROWTH UNDER THE CONSIDERED SCENARIOS (BILLION NOK)

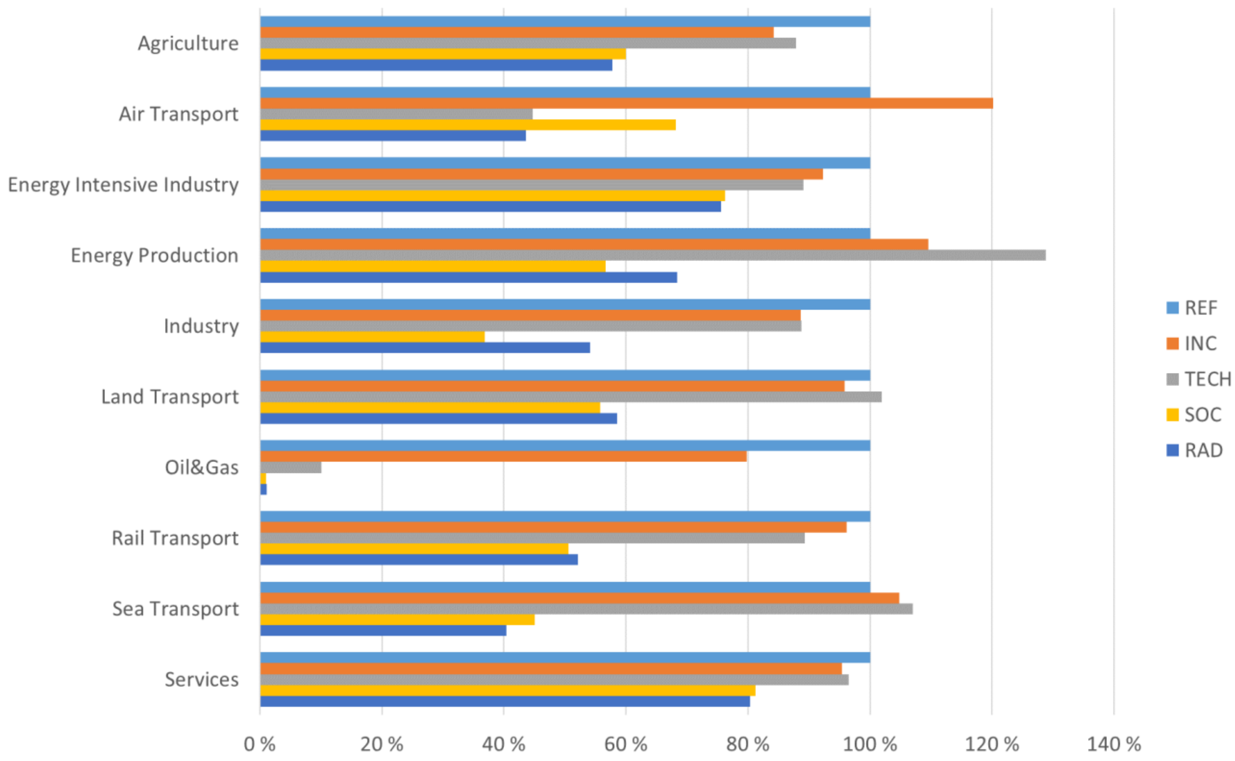

FIGURE 19: VALUE ADDED COMPARED TO REFERENCE IN 2050 PER SECTOR UNDER THE DIFFERENT SCENARIOS

The effects on the sectoral value added are more detailed in Figure 19, where the value added of each sector under each scenario in 2050 is benchmarked to the value added of the same sector under the reference scenario in the same year (which has been normalized to 100%). It is noticeable that the value added for most of the sectors in 2050 is smaller than its counterpart under the reference scenario. Some exceptions, under the scenarios focused on growth and with a projected increase in population, are for the air and sea transport. In particular, under the INC scenario, the air transport experiences a large increase in value added while the sea transport has a higher increase compared to the reference case, but not as strong as for the air transport sector. Under the TECH scenario, it is only the sea transport that experience an increase in value added stronger than the one under reference, albeit in a smaller extent. The air transport sector sees a relatively significant boost in value added under the INC scenario. This is not just because of improvements in the energy mix that cut down on fossil fuel use, but also because the prices of various services taking a large share of the total costs for this sector have stabilized or decreased.

When looking at the main components of the growth, industry and services, we can see that services not only define the largest fraction of the total GDP, but also tend to keep growing in a more pronounced manner in the alternative scenarios compared to industry (Figure 20). To understand why the service sector keeps such a level of growth, and even manages to perform comparably to the Reference under the TECH scenario, we consider a more detailed analysis of what happens to industry and services under the four scenarios. We initially focus on the construction sector, which provides the largest share of value creation for industry, and then we observe what happens to the remaining part of the industry.

Under the SOC scenario, the construction sector requires more labour to continue operating because of the decrease in labour productivity and to the sector's low degree of substitutability between labour and capital. Moreover, there is a general decrease in demand due to the stagnating population growth. This, coupled with a generalized increase in wage rate due to the higher demand for labour to maintain the production level, leads to a general increase in production costs, which make the output of the sector more expensive and leads to a lower demand compared to the Reference scenario. The construction sector keeps growing, but at a much lower pace compared to its potential growth under the Reference scenario. In particular final consumption, energy intensive industries and services reduce remarkably their expenditure for constructions. On the other hand, under the SOC scenario there is a stronger decrease in the cost of capital compared to the other scenarios due to its larger availability after the strong reduction of activity of fossil-based sectors and a lower demand from industry. Nevertheless, the construction sector need labour alongside capital in order to increase its production, and labour becomes very expensive under the SOC scenario. The increase in costs that these changes bring results in a lower demand increase, compared to other scenarios with a price that remains stable at 2023 levels. The lower demand for materials in the economy also contributes to lower the production costs, as it makes these more available. This leads to more demand for labour force which, in turn, asks for steadily higher wage rates, particularly due to the lower availability of workforce in this scenario. The effect is that while profits do not grow particularly towards 2050 for this sector, the compensation distributed for labour by this sector grows, albeit with a lower intensity compared to the reference scenario or to other scenarios with an increase in population and more focused on growth. This growth is allowed by the fact that energy draws only a small portion of the total costs bore by this sector, with materials and labour taking the largest share. Therefore, the construction industry is only mildly impacted by the costs associated with decarbonization, which have its first impact on the cost of energy, compared to other energy intensive sectors.

A different behaviour is displayed by other industrial sectors, whose expenditure in energy inputs has a higher weight on the definition of the total costs. These sectors will experience a larger impact on the production costs by the increase of both costs related to the energy transition, such as the purchase of GHG allowances, and the increase in wage rate. However, the rise in costs cannot be covered by a corresponding increase in prices, primarily because of the independent decline in demand resulting from reduced final consumption for these industries. In fact, constructions are primarily purchased for investment purposes, considering a budget allocation depending on the price of the commodity. Investors benchmark the current price against its potential return, Households, on the other hand, are less likely to change their consumption basket in response to price changes in favour of maintain a more balanced consumption pattern. This means that even if the price of these industrial products decreases, there will not be a strong relative increase in demand. Under the SOC and RAD scenarios there is a shift towards adopting a circular economy model, leading to decreased consumption of manufactured goods. This overall trend leads to higher costs and a subsequent decrease in demand, which in turn causes prices to decrease as a means to counteract the reduced demand. Consequently, the value added for the industry reaches its peak around the year 2040 and subsequently begins to decline. This behaviour is similar under the INC and TECH scenarios, but with the peak being reached much later and only beginning to decrease when approaching 2050 due to the stringent decarbonization requirements. In the TECH scenario, the technological improvements such as the usage of CCS in industry and the continued focus on growth of the society lead to a growth similar to the one followed by the INC scenario which is only mildly different from the Reference except for the stronger policy push towards a decrease in GHG emissions, counterbalanced by the technology improvements on the energy mix from the production sectors.

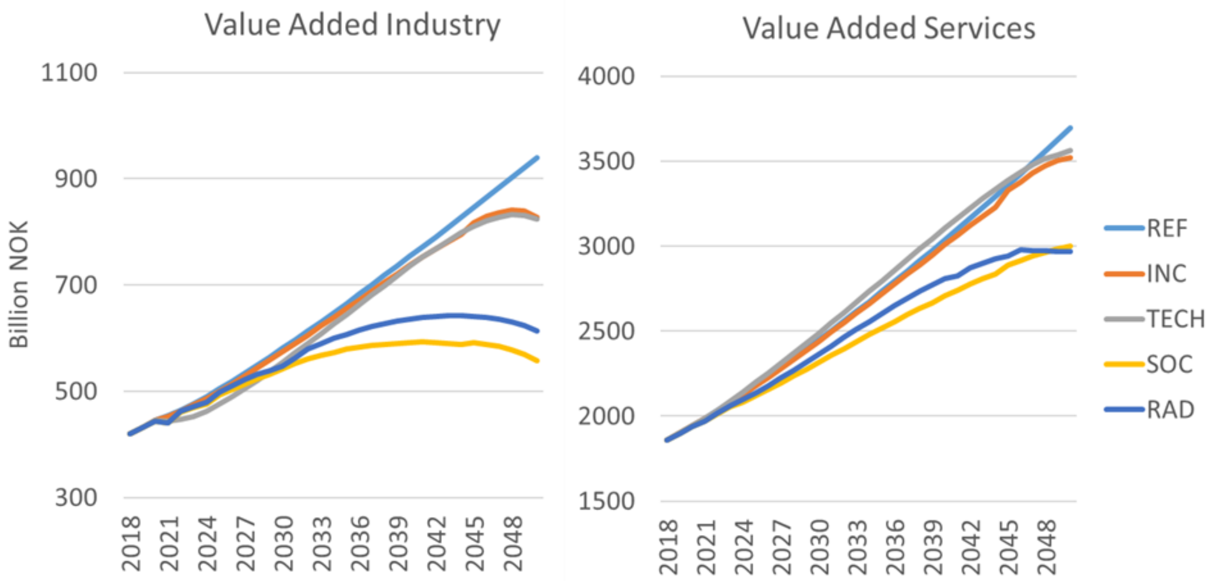

FIGURE 20: DEVELOPMENT OF VALUE ADDED FOR INDUSTRY (LEFT) AND SERVICES (RIGHT) UNDER THE CONSIDERED SCENARIOS

The services sector has a much milder response to the strong changes under the SOC and RAD scenarios. In particular, if we look at the two largest sectors in this category, administrative services and "other" services (mainly financial advisory and financial related services) we can see that under SOC and RAD, the lower economic growth due to the reduced productivity of labour has the effect of decreasing the speed of capital formation due to lower incomes, and therefore lower savings. On the other hand, under these scenarios, capital is also partially being made available from the disinvestments in the oil and gas sector which, together with the reduced economic activity due to the decrease in labour productivity, contributes to maintaining the required return on capital low, even if the overall capital availability is smaller compared to the Reference scenario. This leads to a reduction of investments in some sectors, such as administrative services towards 2050. The lower economic activity implies a lower demand for labour, which will need to accept lower wages to enter the labour market compared to the Reference scenario. Sectors with higher capacity of substituting capital with labour, such as post and telecommunication services, and administrative services, will leverage on this low wage rate and employ more workers compared to the Reference scenario. The sector will manage to afford more employees not only due to the lower wage rate but also thanks to a more intensive purchase of services by the households, which are positive towards the adoption of a circular economy paradigm. This will imply a much milder decrease in demand and will allow for the application of higher prices for these services compared to industrial products. The demand for administrative services will anyway be lower compared to the demand under the Reference scenario. The lower returns on capital and the lower invested capital together with the lower wages will nevertheless make the growth of value added for administrative services weaker than what is experienced under the Reference scenario.

Under the TECH and INC scenarios, the stronger economic growth allows for a faster accumulation of capital, which contributes to larger investments in all the sectors. Services also benefit from this increased availability of capital, which leads to a growth in production of services and a large demand for labour force. In sectors with high capacity of substituting labour with capital, such as in post and telecommunication services, the demand for labour will grow less than proportionally to the growth in activity level for these sectors. In these scenarios, the evolution of prices for services is similar to the one in the Reference scenario, with lower increases compared to the RAD and SOC scenarios, due to the lower level of circular economy. The demand for services grows more under the scenarios displaying a larger growth of the population (TECH and INC) even in absence of a larger adoption of a circular economy paradigm. The relative slower increase in prices for services under INC benefits some sectors like air transport, that is highly relying on the purchase of services.

For what concerns transport sectors, except for air transport, they follow a similar pattern as the ones seen for industry and services, but with a de-growth path for the scenarios SOC and RAD in which there is a joint effect of a general slower economic growth and a smaller population.

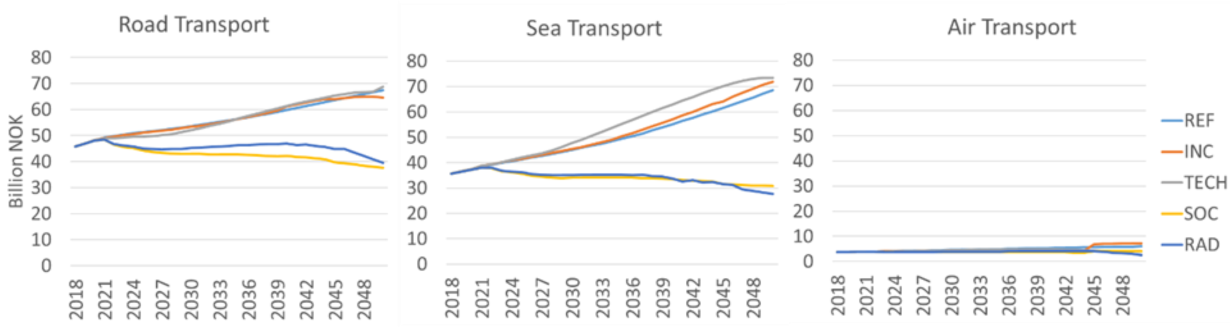

FIGURE 21: DEVELOPMENT OF VALUE ADDED FOR LAND (LEFT), SEA (MIDDLE) AND AIR TRANSPORT (RIGHT)

Transport sectors are characterized by a dominant cost component defined by services, which take around 40-50% of the entire cost and air transport being the sector with the highest expenditure share on services. The generalized increase in costs for services, particularly strong under the SOC and RAD scenario make these sectors less competitive. This coupled with the reduced demand due to the trends emerging in society lead to a decrease in value added. In air transport, services make up about the 75% of the total costs, and this makes this sector very vulnerable to increases in prices for services. The increase in price for services and the generalized increase in wage rate, lead to an increase in price for air transport under every scenario, with a consequent reduction of demand and a decline in value added. This trend breaks around 2040 for air transport under the INC and SOC scenarios due to the elimination of fossil fuels in the transport sector and general slowdown in price increase for administrative services, which constitute a high share of the costs for this sector. Air transport relies strongly on the purchase of services. The increase in price for many administrative services will slow down due to a gradual substitution of labour with cheaper capital and towards 2040 this will grant air transport a higher competitivity. Nevertheless, as the size of this sector is much smaller compared to road or sea transport, the effects on the purchase of energy commodities will be marginal. The result for the air transport will be an inversion in the demand trend, which also will lead to increase in prices. This will in turn lead to a high increase in value added between 2045 and 2050.

Prices and Quantities in REMES-Norway

The REMES-Norway CGE model considers monetary flows in a benchmark year (2018, in our case) as data. These monetary flows are then calibrated with indices for demand and prices, whose value is equal to 1 in correspondence of the benchmark year. Thus, the monetary flow in the basic year is, in principle, defined as follows

$$\bar{P} \times \bar{Q} \times i_P \times i_Q$$

with $\bar{P}$ defining the price in the benchmark year and $\bar{Q}$ defining the quantity in the benchmark year, while i_P and i_Q define the indices for the variations of price and quantity respectively. In the model we are interested on the evolution of indices i_P and i_Q, while $\bar{P} \times \bar{Q}$ represents a flow of money in the benchmark year and its allocation into price and quantity does not need to be known *a priori*. In other words, REMES-Norway (as for any other CGE model) does not consider as input $\bar{P}$ and $\bar{Q}$ separately, but it reads a single figure defining a monetary flow $\bar{F} = \bar{P} \times \bar{Q}$ in the benchmark year. Therefore, any flow of money for a traded commodity is represented in REMES-Norway as

$$F = \bar{F} \times i_P \times i_Q$$

4.2.2 Energy

The economic development of the key elements in the energy system is characterized by a generalized decrease in demand of refined fuels (such as gasoline, diesel, jet fuel), due both to the technological change, fostering a transition towards a clean structure for the production sectors and the policy instruments such as the increase of the CO2 price and the taxation of fossil fuels usage in transport.

Error! Reference source not found. shows (in relative values from 2018) a fast decrease in demand for fossil fuels from industry and final consumption (i.e. the sum of consumption from households, investors and government), while the usage in transport decreases less rapidly in the initial years, especially in the TECH scenario. Prices decrease over time as a result of the reduced demand. The demand for refined fuels does not decrease completely and the residual demand, especially in the INC and TECH scenarios leads to an increase in prices towards 2050. This is also due to the continued population growth towards 2050 under these two scenarios.

Oil, shown in Figure 23, displays an initial increase in demand due to the decrease in price led by the rapid decrease in demand for exports. The price starts growing when the decrease in extractions becomes faster and the environmental constraints implied by the price of GHG emissions are still not stringent; after reaching a peak in the mid-2030s the price starts decreasing again, when the effect of the GHG prices become more important than the effect of the reduced availability of oil in the economy. The demand is decreasing in every sector and the decrease is particularly strong for exports. Demand for consumption is almost completely related to investments.

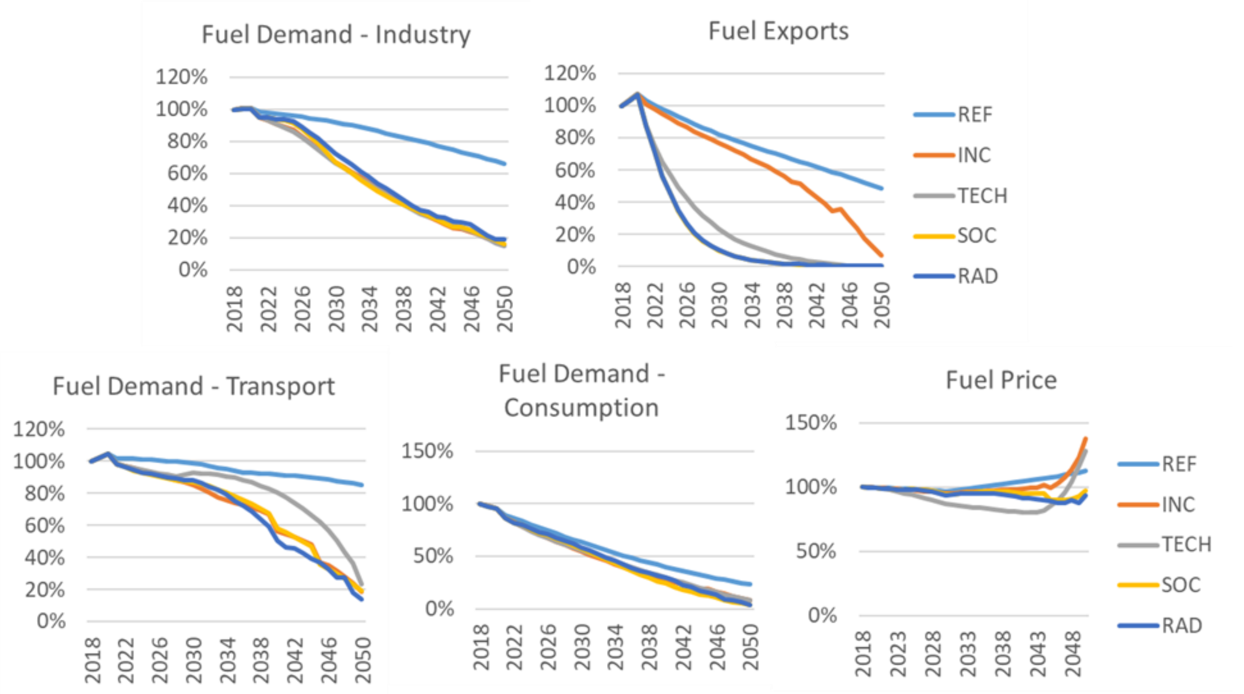

FIGURE 22 INDICES FOR DEMAND AND PRICE OF REFINED FUELS (2018 = 100%)

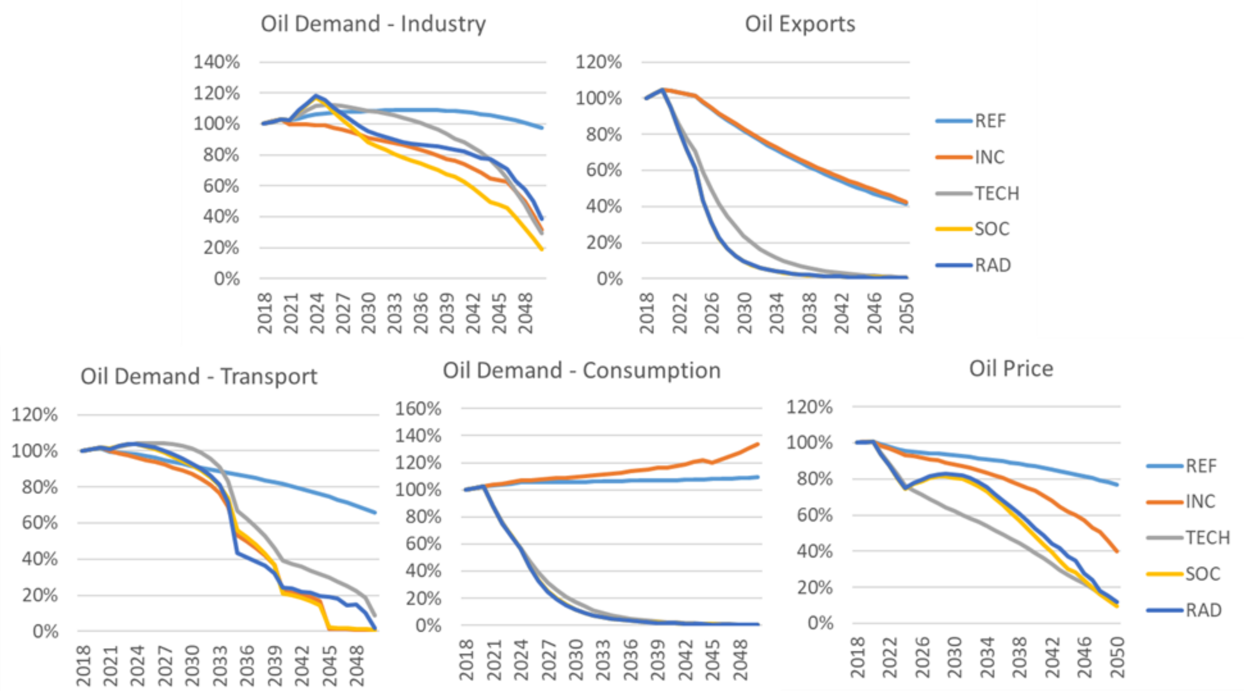

FIGURE 23: INDICES FOR DEMAND AND PRICE OF OIL (2018 = 100%)

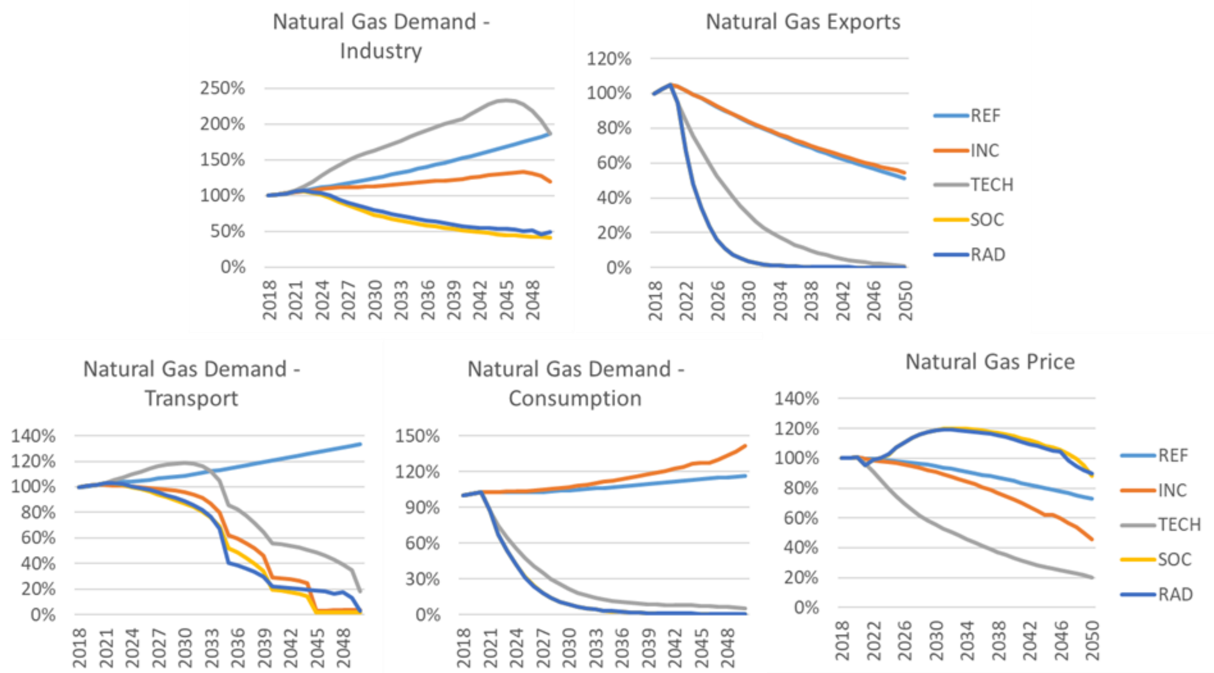

FIGURE 24: INDICES FOR DEMAND AND PRICE OF NATURAL GAS (2018 = 100%)

Gas demand, shown in Figure 24, increases particularly under the TECH scenario for industrial activities such as chemical industries, where gas is used for non-combustion processes, and to produce blue hydrogen, and in industry thanks to the advancements in adoption of CCS. In this scenario, the extractions of gas are kept stable at current levels, which contributes to a strong decrease in prices. On the other hand, the price of natural gas under the SOC and RAD scenario increases after 2025 due to its lower availability due to a fast reduction of the extractive activities coupled with a demand that does not decrease as fast, as it is still used in production of hydrogen and several other applications. The growth curbs after 2030, when the prices for CO2 allowances become high and the demand for fossil fuels starts decreasing. Demand for consumption is almost completely related to investments.

Demand for electricity is shown in Figure 25, where we can see that the industrial demand tends to grow fast in the initial years of the energy transition process, while it decreases in the subsequent years, either due to the uptake of new technologies such as CCS in industry, as under the TECH scenario, or because of a generalized decrease in demand due to lower economic growth, as for the SOC and RAD scenarios. On the other hand, even if the economic growth of the industrial sector is quite modest in the RAD scenario, demand for electricity is higher than under the SOC scenario due to its usage in the production of hydrogen via electrolysis and to the general higher activity for industry led by the technological innovations assumed under this scenario. The increase in demand of electricity in transports is relatively very high compared to 2018, as many transport sectors were not using electricity as fuel but are expected to gradually shift to this commodity as source of energy. The particularly high demand of electricity under the TECH and RAD scenarios lead to a change in the otherwise decreasing prices trend towards 2050 under these scenarios. Prices for electricity are expected to increase as electricity usage becomes more intensive under the scenarios with more focus on growth and high industry activity level, while the prices are expected to decrease under the scenarios with lower focus on growth and with reducing population. In scenarios with a strong oil and gas exports phaseout there is a positive impact on the exports of electric power. The phase-out of oil and gas exports diminishes global demand for Norwegian products, which in turn lowers their value in terms of trade. This relative devaluation of exports compared to imports boosts demand for other goods. This trend is especially pronounced for electricity under the TECH, SOC and RAD scenarios. In the TECH scenario, this increase in demand for electricity from abroad further contributes to an increase in electricity prices towards 2050[1].

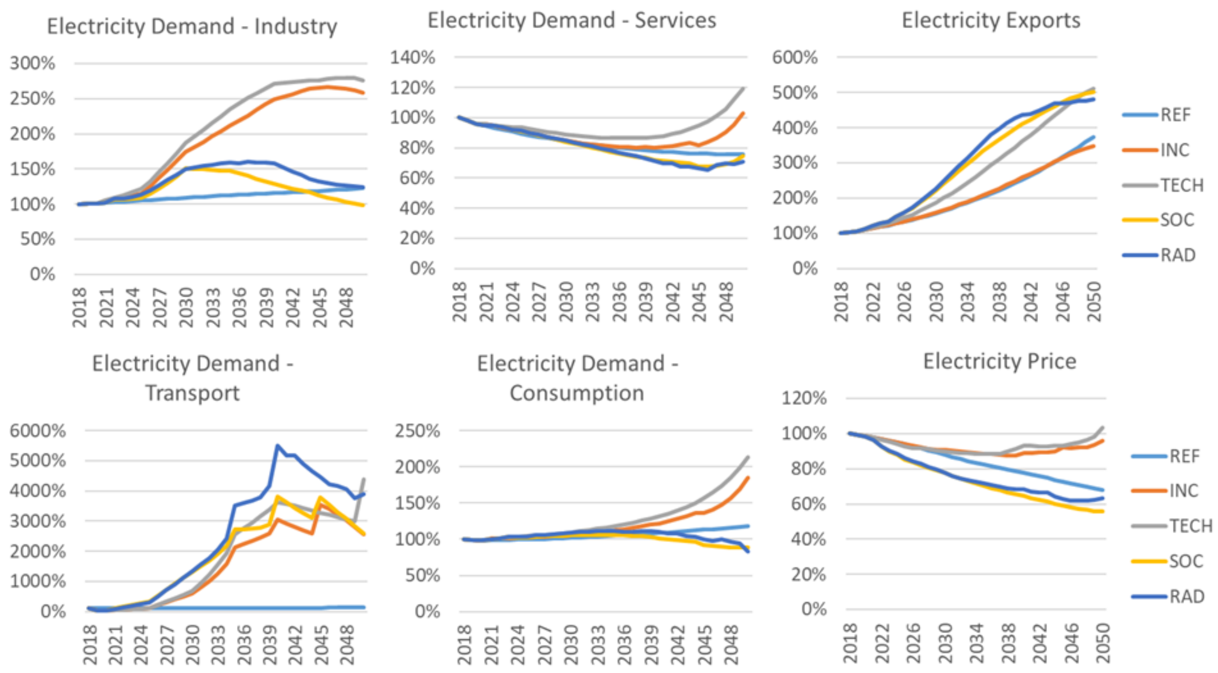

FIGURE 25: INDICES FOR DEMAND AND PRICE OF ELECTRICITY (2018 = 100%)

4.2.3 Labour

To complete the analysis, the following part contains the projections of how the demand for labour changes for the different sectors under the NTRANS scenarios, displayed in Figure 26. We can see that demand for labour under each scenario is expected to be lower than under the reference scenario, with the exception of air transport under the INC scenario, electricity production under all the scenarios focused on growth, and land and sea transport mostly on scenarios focused on growth. Moreover, it is noticeable that the demand for labour follows the growth of the value added for nearly all sectors under the different scenarios. Notice, that the labour demand does not increase particularly under scenarios with stagnating population growth due to lack of labour force. Generally, the decarbonization scenarios analysed in this document lead to a reduction of the economic growth and a lower demand for labour compared to the reference scenario except, under the scenarios based on growth, for energy related sectors such as power production and hydrogen related sectors. Nevertheless, some scenarios, such as TECH keep up with an

[1] It is also possible to notice that electricity demand for transport tends to behave quite erratically after 2040. This is due to the fact that the initial demand for electricity is very small in comparison to the values that it assumes towards the end of the analysis horizon, and this might lead the model to produce solutions that might, for the demand in this particular sector, be a little fuzzy.

employment level comparable to that of the reference scenario, especially for which are large contributors to the overall growth such as Industry or Services and which are responsible for the largest share of employment.

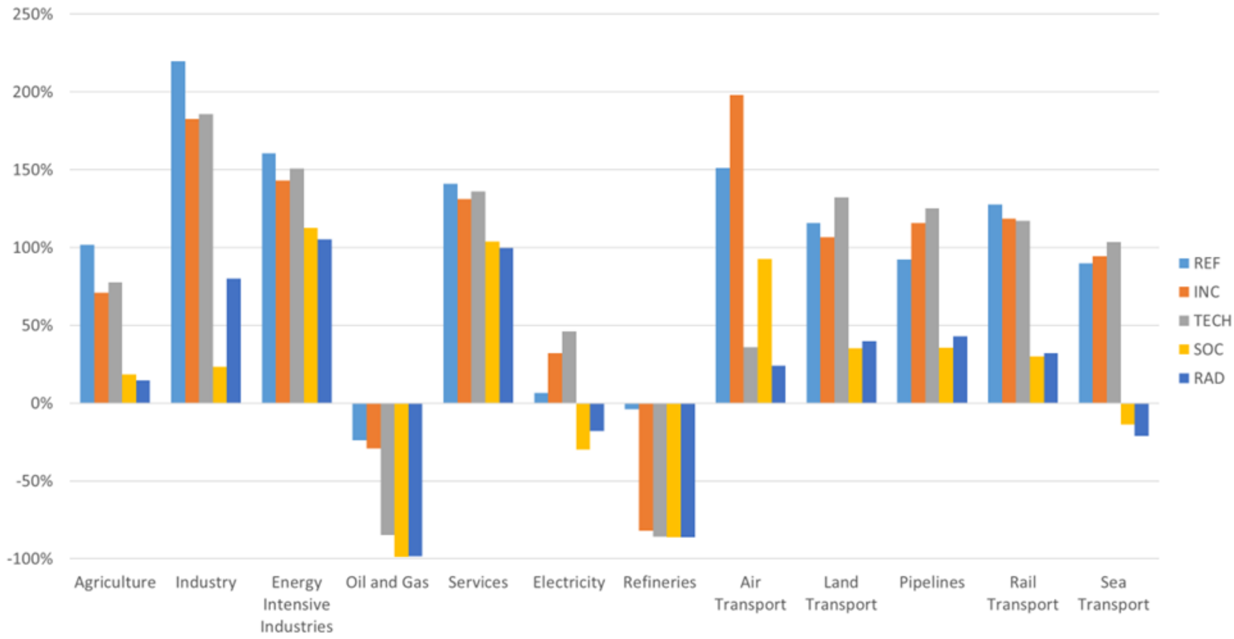

FIGURE 26: LABOUR DEMAND CHANGE COMPARED TO 2018 UNDER THE DIFFERENT SCENARIOS

5. Further work with the 10-step approach

This report describes the three first steps in the NTRANS 10-step approach for sustainable transition pathways. First, the description of the four socio-technical NTRANS scenarios, second, the quantification of the scenarios, and third, the analysis of the four scenarios with the NTRANS models IFE-TIMES-Norway (energy system) and REMES-Norway (regional economy). In parallel with this work, a quantitative and qualitative in-depth study of the maritime sector has been conducted and will be described in separate reports.

The insights from the four scenarios, the analysis and the in-dept study of maritime sector show different sustainable transition pathways in terms of changes in society and technology. None of the four scenarios or pathways are "likely" to happen exactly in the form as they are described in this report. Rather, a key point has been to show that a sustainability transition can be achieved in different ways – and have different kinds of consequences. The form of sustainability transition is dependent, for example, on the actions, choices, values and ambitions of policy makers, citizens, companies, and other societal actors.

To achieve any kind of sustainable transition in the society, a long-term commitment from policy makers and other actors is needed. Some of the challenges for transitions will be addressed in rest of the 10-step approach, where we will focus on critical points and bottlenecks in the transition, such as social acceptance, the need for technology development and access to capital. Researchers in NTRANS will continue the work with identifying important measures to reduce important bottlenecks, and we will include sensitivity analysis to study the impact on uncertain parameters in the models. Based on this we will have a discussion of policy implications from both the socio-technical analysis and the model-based analysis. Finally, the research will be summarized in a scientific paper and a policy paper.

It is a goal that this scenario framework will be further developed in other NTRANS studies. Along with this ten-step approach, a more detailed study of the energy demand projection of different sectors is carried out.

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Appendix A: Energy System Model IFE-TIMES-Norway

The TIMES modelling framework is developed within the ETSAP (the Energy Technology Systems Analysis Program) IEA implementing agreement during several decades (IEA-ETSAP, IEA-ETSAP 2022). TIMES is a bottom-up framework that provides a detailed techno-economic description of resources, energy carriers, conversion technologies and energy demand. The framework is mainly used for medium and long-term analysis on global, national and regional levels, including the Energy Technology Perspectives and World Energy Outlook of IEA. TIMES models minimise the total discounted cost of the energy system to meet the demand for energy services for the analysed model horizon.

IFE-TIMES-Norway is a technology-rich model of the Norwegian energy system divided into five regions corresponding to the current electricity market areas (Haaskjold, Rosenberg et al. 2023). The model provides operational and investment decisions from the starting year, 2018, towards 2050, with model periods for every fifth year from 2020 to 2050. To capture operational variations in energy generation and end use, each model period is divided into 96 sub-annual time slices, where the four seasons are represented by one day of 24 hours in each season. IFE-TIMES-Norway minimizes the total discounted cost of the energy system in meeting the Norwegian demand for energy services for the period 2018-2050. The energy system cost includes investment expenditures in supply and demand technologies, storage technologies and transmission lines, operation and maintenance costs, and costs of net electricity imports.

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

The use of electricity, hydrogen, district heating and biofuels are examples of operational decision variables. Consequently, the marginal prices of these energy carriers are a model result. Petroleum products and imported biofuels are examples of energy carriers that are determined outside the model, i.e., exogenously.

Appendix B: The REMES-Norway model and its Reference Scenario

REMES-Norway is a macroeconomic model that spans from 2018 to 2050. It has been developed by the Department for Industrial Economics and Technology Management at the Norwegian University of Science and Technology and SINTEF. The model specifically looks at Norway's five electricity price regions and evaluates policies related to energy, decarbonization and sustainability. It includes factors like CO2 pricing and natural resource availability for extraction industries.

The model is coded in GAMS and uses the MPSGE toolbox, eliminating the need for a full algebraic formulation. A graphical representation of the model's structure is available in Figure 27.

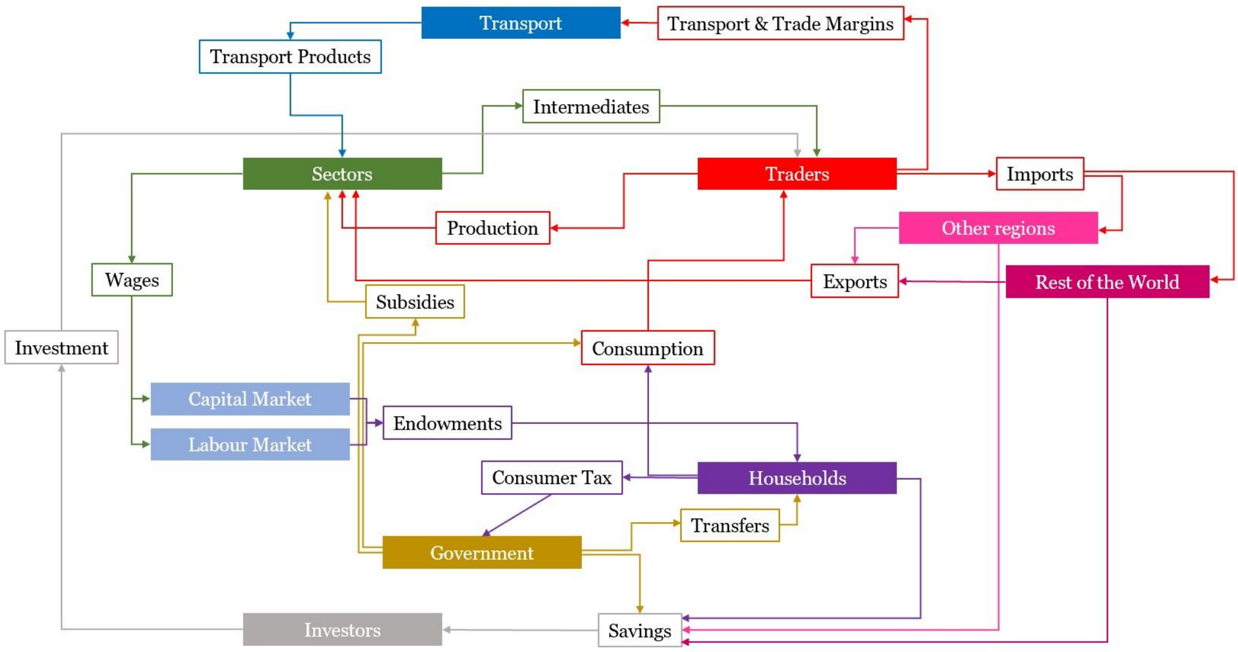

FIGURE 27: MONETARY FLOWS IN REMES-NORWAY

In the model, households represent the total consumption in each region. They buy goods from traders and pay taxes to the government, while their savings go to investors. Their income comes from capital, labour, and government transfers. The government collects taxes and spends money on goods from traders, sector subsidies, and household transfers. Investors use savings from both the government and households to buy goods and services, representing the economy's investment.

Sectors in the model produce goods and services, which are bought by traders. These sectors also purchase intermediate products from traders. Traders serve as a hub that combines different types of the same good, like exports and domestic production, into a single variety for regional consumption. Some of the goods produced by sectors are exported to other regions and internationally.

Households receive wages and capital repayments from these sectors, which make up their income. Traders also handle imports and incorporate them into the goods and services they sell. They add a retail markup, which goes to the transport sector. The transport sector buys materials and energy from other sectors and employs capital and labor from households.

Sectors, Households, Government, Investors, Transport as well as Other regions and Rest of The World follow given behavioural rules to define their demand or supply of commodities. These rules are defined by means of production functions (for production Sectors and Transport, and Traders) and utility functions (for Households, Government, Investors, Other regions and the Rest of The World). These functions define the preferred consumption mix of the aforementioned agents for different type of goods and services for a given set of prices. An important feature of these function is the extent in which they allow for a good to substitute other goods to obtain the same amount of production or the same amount of consumers satisfaction. The extent in which a good can substitute other goods is given by a parameter called elasticity of substitution. The higher the value of the elasticity, the more flexibility a given agent has in terms of consumption choice. Typically, commodities are aggregated into groups based on the need they satisfy or the stage they cover in the production process. For a production function, services and goods are aggregated into the "materials" nest and assigned an elasticity of substitution to define how much these materials are mutually substitutable. Further, energy commodities are grouped into an "energy" nest and, just as for materials, they are assigned an elasticity of substitution, to define how much a given agent, (usually a production sector) might be able to be flexible in the choice of the energy mix. Another group that is normally considered is the one comprising capital and labour, which are paired into a common nest and assigned their elasticity of substitution. These nests are further aggregated into other nests, normally aggregating the capital-labour nest with the energy nest, equipping them with an elasticity of substitution to define to what extent the capital and labour aggregate can substitute the energy aggregate. After creating the new aggregate containing capital, labour, and energy, this aggregate is further nested with materials using another elasticity of substitution. The output of the function (the final aggregate) is scaled to obtain the output of the considered sector in the benchmark year. A typical production structure for a sector in REMES-Norway is displayed in Figure 28, where the different σ define the elasticities of substitution in the different nests. Based on the diagram, capital (K) and labour (L) are initially nested using elasticity of substitution σ_{KL}, while in the energy nest, fossil fuels are aggregated with emission allowances with a zero elasticity nest (i.e. they need to be purchased in fixed mix, depending on the emissions that the particular fuel produces in the given sector), while electricity and gas need to be purchased together with power transmission and pipelines transmission services, respectively. The energy commodities are bundled in the energy nest using elasticity σ_E. Materials are bundled using elasticity σ_M. Capital and labour are aggregated together with energy commodities into a nest which is assigned elasticity σ_{KLE}, finally the aggregate capital, labour, and energy is aggregated with materials into a nest with elasticity σ_{KLEM}. This structure provides the behavioral rules for the sector to decide its inputs and how these inputs change as the prices change. Prices will change to ensure that when each sector and actor formulate their consumption and production decisions, the demand of each good, service and resource correspond to the supply.

Elasticities of substitution used in CGE models like REMES-Norway are typically taken from past studies and surveys and are subject to some variability among studies. For sectors that do are currently not economically profitable and therefore not yet present in the economy in large scale these elasticities might not exist and need to be identified in other ways, such as with experts elicitation or using elasticities taken from sectors that are considered similar to the one that needs to be introduced. Very often elasticities might be not acceptable to be used to model some sectors and experts feedback is very important to be able to refine the responses of the model.

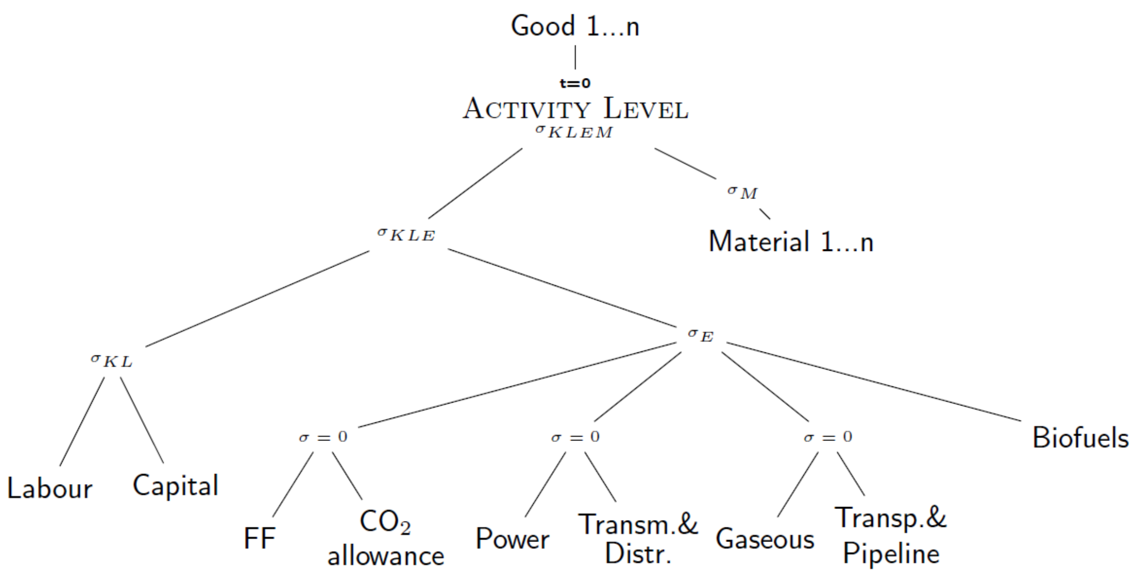

FIGURE 28: TYPICAL PRODUCTION STRUCTURE OF A SECTOR IN REMES-NORWAY

Further, the text outlines the steps taken to model the reference scenario and to modify the relevant parameters to reflect the alternative scenarios outlined for the project.

The first step in modelling the decarbonization scenarios was to define a reference scenario. The goal of defining a reference scenario for CGE models is to provide a baseline against which alternative scenarios can be compared. The reference scenario represents a projection of what is likely to happen in the future if current trends continue, based on available data and assumptions about the economy. This scenario is usually calibrated to match historical trends and recent forecasts and is used as a starting point for modelling the effects of different policy or market changes. By defining a reference scenario, CGE models can provide a comprehensive view of the economy, including inter-sectoral linkages, and how policies or changes in one sector can affect the entire economy. Alternative scenarios can then be modelled by modifying the relevant parameters in the reference scenario, such as changes in technology or policies. Equipping the model with a reference scenario allows to have a common starting point for modelling and comparing alternative scenarios besides enabling a better understanding of the potential consequences of different policy choices.

The reference scenario was modelled using data from various sources, including the "Long-term Perspectives on the Norwegian Economy 2021" document (Norwegian Ministry of Finance 2020), The Norwegian Water Resources and Energy Directorate (NVE 2021), and growth projections from the statistical central bureau (Statistics Norway 2022). The GDP growth in the reference scenario was calibrated to match that of the "Long-term Perspectives on the Norwegian Economy 2021", using the “2021 white paper baseline” path, shown in Figure 29.

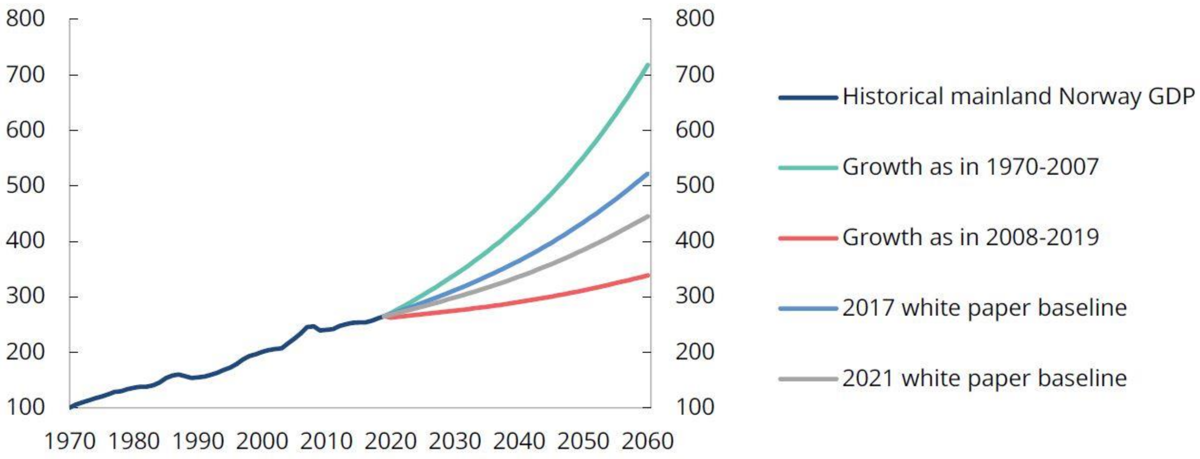

FIGURE 29: GDP PROJECTIONS IN THE "LONG-TERM PERSPECTIVES ON THE NORWEGIAN ECONOMY 2021" DOCUMENT. THE 2021 WHITE PAPER BASELINE ESTIMATION HAS BEEN USED TO CALIBRATE THE GDP GROWTH OF THE REFERENCE SCENARIO (SOURCE: LONG-TERM PERSPECTIVES ON THE NORWEGIAN ECONOM

The population growth has been derived from the MMMM-alternative provided by SSB, while the development of energy demand was obtained from data made available by The Norwegian Water Resources and Energy Directorate (NVE 2021) considering a growth rate consistent with 210 TWh in 2000 and 225 TWh in 2014, as shown in Figure 30. Moreover, further data from NVE (NVE 2018) has been used to estimate the development of electricity consumption, set at 0.49% per year. This growth has been factored into the model by defining an electricity specific multiplier on the demand side – i.e. in the production functions of the sectors, and specifically on the electricity demand input – which is calibrated to ensure that the demand of electricity grows following the estimated consumption growth rate under the reference scenario.

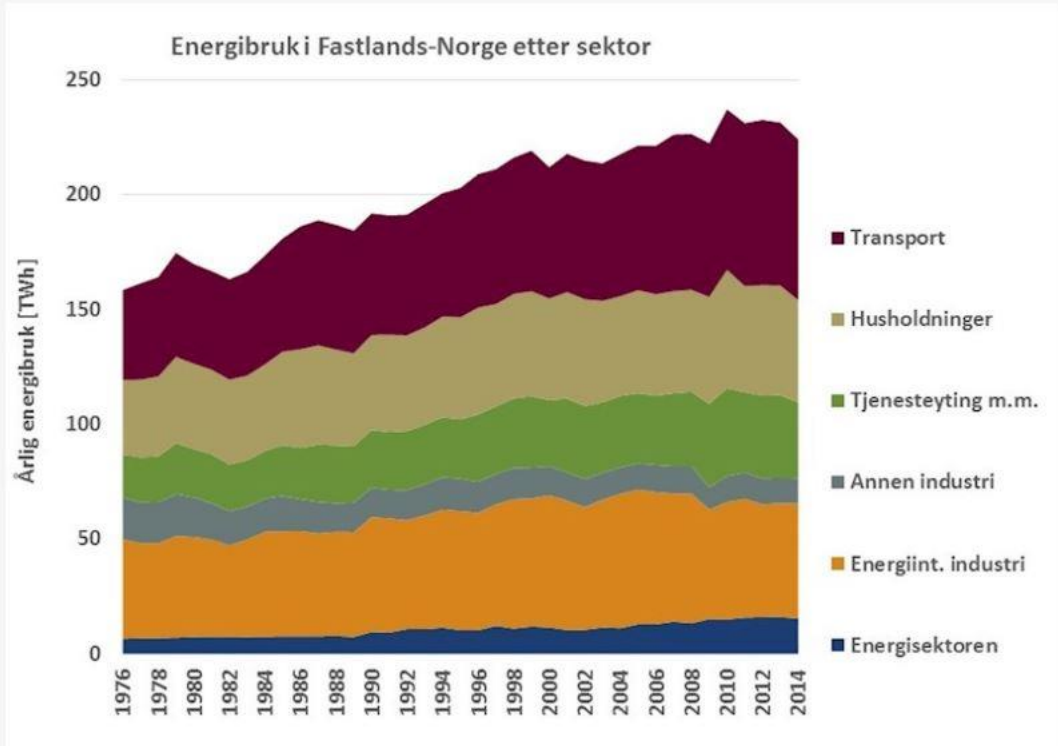

FIGURE 30: SECTORAL ENERGY DEMAND IN NORWAY USED TO ESTIMATE THE ENERGY DEMAND GROWTH RATE TO BE APPLIED UNDER THE REFERENCE SCENARIO (SOURCE: HTTPS://WWW.NVE.NO/ENERGY-CONSUMPTION-AND-EFFICIENCY/ENERGY-CONSUMPTION-IN-NORWAY/ (A))

The projected energy consumption growth from The Norwegian Water Resources and Energy Directorate and the projected GDP growth are used to obtain the yearly energy intensity in the economy. This allows for the description of how the requirements for energy per unit of GDP decrease over time due to technological improvements.

On the resources side, the extraction of oil is assumed to start decreasing by 1.94% yearly towards 2030 only starting from 2024, as shown in Figure 31, following the "PM21" path.

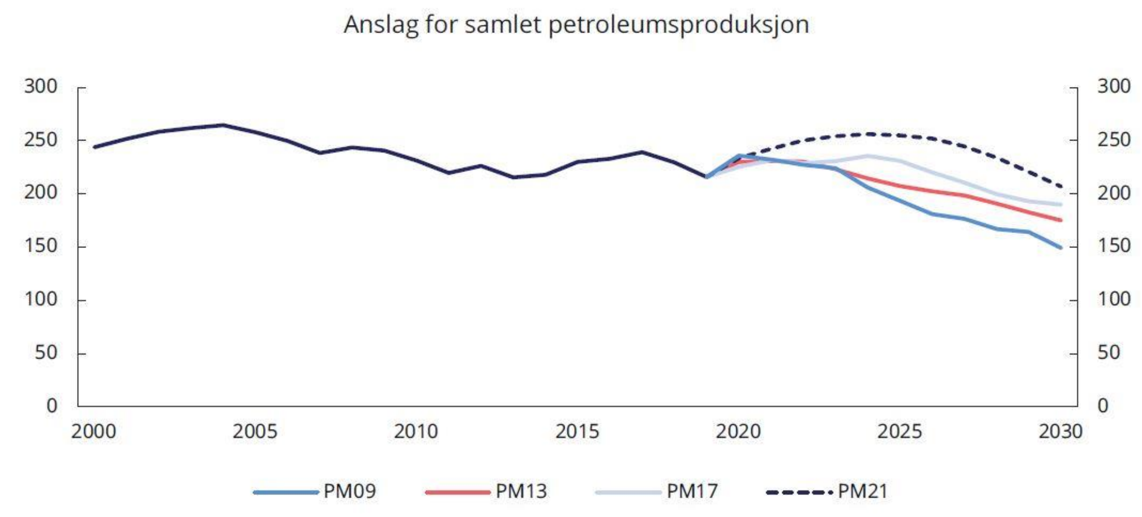

FIGURE 31: DEVELOPMENT OF OIL EXTRACTION BETWEEN 2000 AND 2020. PROJECTION FROM 2020 TO 2030. THE PROJECTION PROVIDED BY THE PM21 PATH BETWEEN 2024 AND 2030 HAS BEEN ASSUMED TO BE THE

TREND FROM 2024 TOWARDS 2050 IN THE REFERENCE SCENARIO (SOURCE: LONG-TERM PERSPECTIVES ON THE NORWEGIAN ECONOMY 2021.)

GHG emissions under the reference scenario are assumed to decrease by 2.2% per year starting from 2020, as shown in Figure 32 (based on the “National Budget 2021” path), which leads to a decrease in emissions by around 50% between 2020 and 2050.

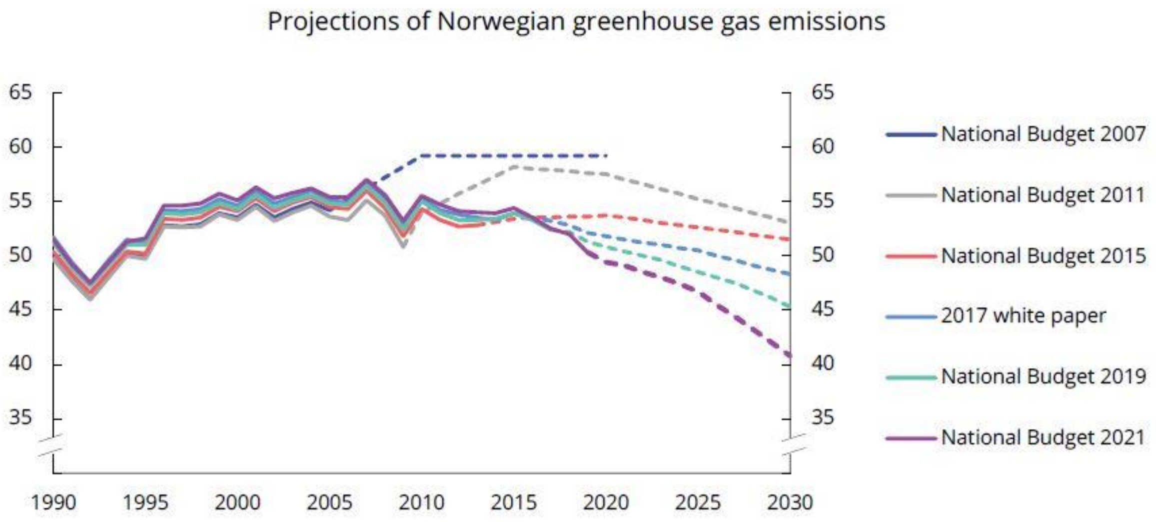

FIGURE 32: HISTORICAL GREENHOUSE GAS EMISSIONS BETWEEN 1990 AND 2015 AND FURTHER PROJECTIONS TOWARDS 2030. THE NATIONAL BUDGET 2021 PATH HAS BEEN USED TO CALIBRATE THE DECREASE IN GHG EMISSIONS TOWARDS 2050 UNDER THE REFERENCE SCENARIO (SOURCE: LONG-TERM PERSPECTIVES ON THE NORWEGIAN ECONOMY 2021.)

The productivity levels for different sectors were also calibrated into the model, using data from the OECD ("OECD Going for growth Norway 2017") and the document "The Norwegian productivity puzzle – not so puzzling after all?", by the Statistic Central Bureau. In this case each sector has been assigned a penalty factor to reduce its productivity to a given percentage of the overall Total Factor Productivity (TFP) in order to differentiate their contribution to the overall economic system. More precisely, the following penalty factors have been used:

Total Factor Productivity penalty multipliers	
Agriculture, forestry and fishing	51.5
Manufacturing	47.2
Construction	78.5
Wholesale and retail trade	95.4
Transportation and storage	51.8
Information and communication	98.3
Financial and insurance activities	61.2

If we denote as ρ_i as the TFP penalty multiplier, and ρ^T as a calibration parameter set at the same value for all the sectors, then the way GDP is calibrated for the reference scenario is by setting the product $\rho_i\rho^T$ as the specific sector productivity and find the level of ρ^T that ensures the GDP to grow as described in the Long-term Perspectives on the Norwegian Economy 2021.

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