Transition Pathways for a Low-Carbon Norway: Bridging Socio-technical and Energy System Analyses

Miguel Chang, Kari Espegren, Kristina Haaskjold, Eva Rosenberg, Sigrid Damman, Tuukka Mäkitie, Paolo Pisciella, Allan Dahl Andersen, and Tomas Moe Skjølsvold

Abstract This study presents an interdisciplinary approach to analyze different transition pathways towards the sustainable development of a low-carbon society, focusing on Norway as a case. The study bridges a socio-technical perspective on sustainability transitions with techno-economic energy systems and regional-economic modelling analyses. Incorporating a socio-technical perspective in the scenario design allows us to envision pathways considering causal processes of technological and socio-institutional change, and potential transition bottlenecks.

M. Chang · K. Espegren (✉) · K. Haaskjold · E. Rosenberg
Institute for Energy Technology (IFE), Kjeller, Norway
e-mail: Miguel.Chang@ife.no; Kari.Espegren@ife.no; kristina.haaskjold@ife.no; Eva.Rosenberg@ife.no

S. Damman
Department of Technology Management, SINTEF Digital, Trondheim, Norway
e-mail: Sigrid.Damman@sintef.no

T. Mäkitie
Department of Technology Management, SINTEF Digital, Trondheim, Norway

TIK Centre for Innovation, Technology and Culture, University of Oslo, Oslo, Norway
e-mail: Tuukka.Makitie@sintef.no

P. Pisciella
Department of Industrial Economics and Technology Management, NTNU – Norwegian University of Science and Technology, Trondheim, Norway
e-mail: Paolo.Pisciella@ntnu.no

A. D. Andersen
TIK Centre for Innovation, Technology and Culture, University of Oslo, Oslo, Norway

Department of Food and Resource Economics, University of Copenhagen, Copenhagen, Denmark
e-mail: Allanda@tik.uio.no

T. M. Skjølsvold
Department of Interdisciplinary Studies of Culture, NTNU, Trondheim, Norway
e-mail: Tomas.Skjolsvold@ntnu.no

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The resulting scenarios are used in the techno-economic energy system analysis to show cost-optimal energy system configurations, including varying levels of new renewable capacity needed, new conversion technologies, and fuel substitutions across all sectors leading to different decarbonization pathways for the Norwegian energy system by 2050. The regional-economy analysis addresses the impacts of these pathways on general economic growth and labor. The results show that higher levels of decarbonization are possible for Norway; however, potential bottlenecks can slow down the transition, while trade-offs in economic growth and development must be balanced out with decarbonization ambitions.

Key Messages

- Linking socio-technical perspectives with energy systems & economic modelling analyses helps providing a holistic framework to assess the feasibility of the energy transition.
- Transition bottlenecks—such as the maturity of technology options, feasibility of novel innovations and infrastructure, and policy developments—are identified across four envisioned scenarios for Norway.
- Cost-optimal energy system designs show varying levels of decarbonization potential.
- Trade-offs between SDG targets, namely economic growth and decarbonization, emerge when considering the degree of socio-technical change under different transition pathways of the energy system.

1 Introduction

The decarbonization of the energy system is expected to play a major role in achieving global climate action targets and contributing to the development of a more sustainable society (IPCC 2022). As part of the global Sustainable Development Goals (SDGs), nations worldwide have committed to providing access to affordable and clean energy (SDG 7) as well as promoting sustainable economic growth (SDG 8), industrialization and innovation (SDG 9), ensuring responsible consumption and production patterns (SDG 12) and undertaking climate action (SDG 13) (UN 2023). Reaching these goals by mid-century will require a rapid and comprehensive net-zero transition which likely involves adopting novel technologies and infrastructures, innovations and reorientation in companies, building new low-carbon value chains, and deep changes in behavior and culture (Andersen et al. 2023a).

Intrinsically, understanding how this transition will take place also requires increased knowledge of how technical developments in national energy systems are affected by the underlying societal, institutional, and organizational structures and policies. Exploring these aspects can therefore provide new insight into the different challenges occurring as the transition unfolds and outlooks of potential pathways for a low-carbon society. Therefore, quantifying the impacts of these elements along the transition can enhance quantitative analyses of the energy system, facilitate planning, and provide better and practical decision support that would not necessarily be considered solely under a techno-economic perspective (Bolwig et al. 2019).

The process of planning the transition towards a sustainable energy system relies on mathematical models to quantify the impacts of different energy transition pathways while capturing the complex interactions within the energy system (Prina et al. 2020; Chang et al. 2021). These modelling tools often have a techno-economic perspective that captures the technical details and flows from supply technologies to end-use sectors.

However, recent studies emphasize the need to better integrate the social dimension in energy system modelling approaches (Trutnevyte et al. 2019; Krumm et al. 2022; Süsser et al. 2022). In turn, this can improve the relevance of modelled transition pathways and more adequately capture the social dynamics that drive or constrain the required changes in the energy system. Indeed, including a socio-technical perspective can also provide a more realistic understanding of the transition with practical implications of technological innovation, and societal and institutional change as society moves towards a sustainable future (Köhler et al. 2019). The integration of quantitative modelling and socio-technical studies, as argued by Turnheim et al. (2015), can thus provide a richer and more robust analytical approach to inform and provide guidance to decision-making.

Previous studies have investigated linking socio-technical transition research and energy system modelling. For instance, Li et al. (2015) highlight the need for more integrative approaches as socio-technical factors are often not captured in quantitative modelling. A systematic review by Hirt et al. (2020) outlines that only a small fraction of studies (~12%) considered the whole energy system, while sectoral models are more frequently aligned with socio-technical transition models.

Other recent studies also follow integrative approaches while looking more coarsely at the whole energy system rather than integrating bottom-up technological details. For example, these studies align socio-technical transition insights with integrated assessment models (IAMs) for European analyses (van Sluisveld et al. 2020), or propose socio-technical scenarios to IAMs for analyzing the energy transition in the UK (Freeman and Pye 2022).

However, as suggested by Geels et al. (2016), IAM's are not always sufficiently suited to provide national and local insight, due to their large global coverage and simplified representation of the energy system. Tailored knowledge accommodating sectoral detail and insight on the economy is needed, along with a necessary understanding of transition dynamics in order to support climate action and to address knowledge needs of policymakers at the national level. Some recent work partly addresses this, bridging energy system modelling and transition studies at the European level but without capturing the broader impacts on the economy (Hainsch et al. 2022). Although studies linking energy system and economic models can be found in the literature (Chang et al. 2023), e.g. linking bottom-up ESMs and CGE models of Norway (Helgesen et al. 2018), these do not purposefully align with socio-technical transition theories (Markard et al. 2012) in their study designs. On the other hand, other studies which align quantitative modelling with socio-technical research do not take a holistic view of the entire energy system, but rather explore the transition in specific sectors, such as the power (Rogge et al. 2020) or heating sectors (Nilsson et al. 2020).

The present study addresses these gaps, providing an approach that bridges socio-technical research and bottom-up analysis of the energy system including all end-use sectors and the economy, taking Norway as a case. This approach allows for a recursive dialogue between models and qualitative storylines, to fine-tune and provide complementary insight from both quantitative and qualitative methods. In turn, the different scenarios provide potential outlooks of sustainable energy system transitions, while capturing different drivers for change and bottlenecks along the transition pathways and their impact on economic development in line with sustainable development goals.

This chapter presents an applied interdisciplinary study, taking Norway's energy system as a case. We combine a socio-technical transition perspective with scenario design applied to techno-economic energy systems and regional economic analyses. Socio-technical transition research is used to envisage contrasting transition pathways for Norway's energy system as well as to evaluate the socio-technical feasibility of transition pathways in terms of governance (Turnheim and Nykvist 2019). The resulting pathways are quantified and incorporated as scenarios into both a long-term energy system model (ESM) in the IFE-TIMES-Norway model (Haaskjold et al. 2023), and in the computable general equilibrium (CGE) model REMES-Norway (Werner et al. 2017). Respectively, the analyses in these models provide a bottom-up representation of the energy system and a representation of the wider effects of the different energy transition pathways on economic development.

The remaining of this chapter presents the following: Section 2 describes the overarching approach and the methods used. Section 3 presents the envisaged transition pathways, providing both a qualitative and quantitative description of the different scenarios. Section 4 presents the results of the analysis, followed by a discussion on these and other general implications in Sect. 5. Finally, Sect. 6 presents the conclusions of the study.

2 Approach and Methods

This section presents the key methods used in the scenario design and quantitative analyses with energy systems and economic models. The analyses were developed as part of the work in the Norwegian Centre for Energy Transition Strategies (FME NTRANS n.d.) and consist of a 10-step approach bridging socio-technical research with techno-economic analyses. The basis of this 10-step approach and the analyses are presented in further detail by Espegren et al. (2023).

2.1 Envisioning Socio-technical Transition Pathways

The scenario development was based on identifying pathways for the Norwegian energy system with contrasting degrees of disruption to the existing socio-technical regime and its central institutions. As suggested by Andersen et al. (2023b), the depth of system change can be distinguished in two dimensions: socio-institutional and technological. Thus, the scenarios considered combinations of minor and major system changes across these dimensions resulting in four pathways:

- Incremental Innovation (INC) pathway: minor system change in both dimensions
- Technological Substitution (TECH) pathway: major technological change and minor socio-institutional change
- Social Change (SOC) pathway: major socio-institutional change and minor technological change
- Radical Transformation (RAD) pathway: major change in both dimensions

Each of the proposed pathways is thus associated with a different type of system change. These pathways manifest in different ways. Minor technological change is linked to decarbonization mainly through core technologies that are largely compatible with the existing value chains, including biofuels, electrification, and energy-efficiency, while major technological change features novel technologies such as hydrogen, ammonia and carbon capture and storage (CCS), requiring novel value chains. Meanwhile, the socio-institutional dimension considers, e.g., the degree of change in population's values and lifestyles. The kind of system change in this pathway is also linked, for example, to changes in the actor networks in energy systems, and the kind and depth of institutional change (regulations, norms, and cognitions). Moreover, transformative pressures at a wider societal level are embedded in these pathways—for example, long-term trends related of demographics, projected demand for energy services, climate change, and societal preferences. The four pathways are elaborated in Sect. 3.

Based on the visions and qualitative descriptions of the four different pathways, key quantifiable factors were mapped to be used as base assumptions in the modelling analyses. The quantification of the scenarios covered factors such as projected energy demand developments per sector, supply and end-use technology data, limitations on energy production and transmission, resource availability, CO_2 costs and targets, and energy prices. Further refinement of these pathways included recursive inputs from the modelling analyses and project partners.

2.2 Energy-Economy Modelling

To assess the impacts of the different transition pathway scenarios considered, the IFE-TIMES-Norway (Haaskjold et al. 2023) and REMES-Norway (Werner et al. 2017) models were used. The IFE-TIMES-Norway provides a long-term cost optimal bottom-up representation of the energy system designs for Norway, providing investment decisions to meet energy demands in all use sectors. Meanwhile, REMES-Norway is a CGE model capable of detecting the impacts of changes in the energy sector in the overall economy.

2.2.1 Energy System Analysis with IFE-TIMES-Norway

IFE-TIMES-Norway is a technology-rich bottom-up model of the Norwegian energy system (Haaskjold et al. 2023), based on the TIMES modelling framework (Loulou et al. 2016). The model represents Norway's energy system as five regions corresponding to the current electricity market areas and includes the different end-use sectors and their corresponding demands for energy services. The model provides operational and investment decisions starting from the year 2018 to 2050 in five-year periods 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 (24 hours for a representative day in each of the four seasons).

IFE-TIMES-Norway minimizes the total discounted system costs of the energy system, including investments in supply and demand technologies, storages and transmission capacity, operation and maintenance costs, and costs of net electricity imports. The main model inputs include fuel prices, electricity prices from countries with transmission capacity connected to Norway, renewable resources, and technology characteristics such as costs, efficiencies, potentials, and technology learning curves using the Norwegian kroner (NOK) as monetary unit (exchange rate of 1 NOK = 0.1 EUR). As outputs, the model provides the optimal mix of supply capacity, and use of energy carriers and end-use technologies to meet energy service demands.

A sensitivity analysis was included in the study to address uncertainty in key input assumptions associated with the quantification of the pathways and scenarios. These uncertainties also characterize to an extent potential transition bottlenecks.

For example, uncertainty in future technology costs can have an apparent impact in modelling results, while simultaneously portraying challenges in technology deployment and consequent technology learning rates along the transition. Intrinsically, these considerations align with transition bottlenecks, further explained in Sect. 3.2, related to the maturity of options and the fit of innovations in the socio-technical system and its infrastructure. Likewise, analyzing the sensitivity of biofuel import prices or CO_2 price assumptions addresses the parametric uncertainty of these inputs while also portraying the potential effect of transformative pressures at a societal level regarding global resource availability and institutional preferences related to adopting policy measures. As such, these assumptions expand the perspectives of the societal and political feasibility of decarbonization options, illustrating how biofuel availability and CO_2 pricing act as potential transition bottlenecks. In the energy system analysis conducted with IFE-TIMES-Norway, the sensitivity analysis included the following parameters:

- Biofuel price increases in SOC and INC, which rely most heavily on biofuel replacements.
- Higher investment costs in later years, representing slower technology learning, in the TECH and RAD scenarios which have higher learning rates and adoption of new technologies.
- High CO_2 prices development (based on values from Regjeringen 2022a) across all four scenarios.

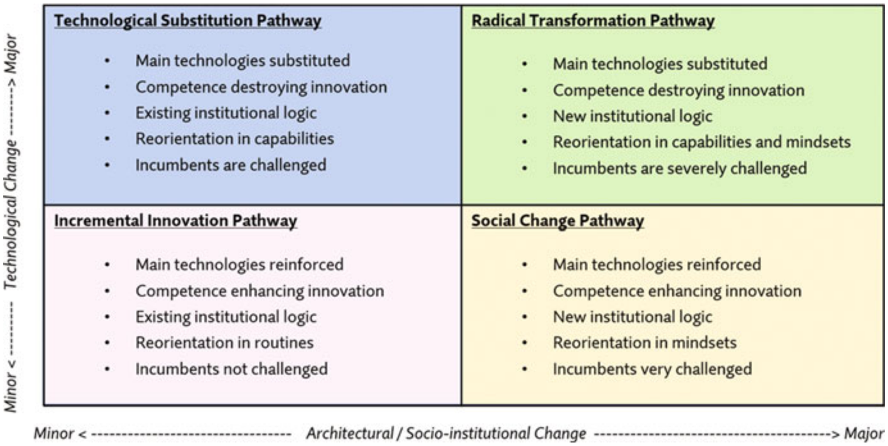
2.2.2 Regional Economic Analysis with REMES-Norway

The CGE model REMES-Norway (Werner et al. 2017) has been used to assess the macro-economic impacts of the various transition pathways. The REMES-Norway model provides a multi-regional multi-sectoral representation of the economy, spanning from the year 2018 to 2050. REMES-Norway is used to analyze the possible responses of the economy to policy measures or technology innovations.

In the current study, eight main factors characterizing the development of the economy were used as basis for capturing the impacts of the four scenarios considered. These factors included: population, productivity, technology, energy intensity, resource deployment, resource export, shift to a circular economy, and transportation development (Espegren et al. 2023). The model results provide a view of projected trends such as GDP development, labor change and value added across key sectors of the economy, and price and demand indices for energy commodities. The energy use by technologies 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. From the resulting outputs, no additional data feedback is provided back to the IFE-TIMES-Norway energy system model.

3 Socio-technical Scenarios Definition, Quantifications and Bottlenecks

This section presents a brief overview of the four transition pathways considered in the scenario analysis. These scenarios portray pathways with contrasting degrees of socio-institutional and technical change, as illustrated in Fig. 1. In the following sections, further description of the different scenarios is provided as well as an overview of key parameters quantified for each scenario. Further detail of these scenarios and quantification of input assumptions is provided in the project report for NTRANS (Espegren et al. 2023).



Technological Substitution Pathway • Main technologies substituted • Competence destroying innovation • Existing institutional logic • Reorientation in capabilities • Incumbents are challenged	**Radical Transformation Pathway** • Main technologies substituted • Competence destroying innovation • New institutional logic • Reorientation in capabilities and mindsets • Incumbents are severely challenged
Incremental Innovation Pathway • Main technologies reinforced • Competence enhancing innovation • Existing institutional logic • Reorientation in routines • Incumbents not challenged	**Social Change Pathway** • Main technologies reinforced • Competence enhancing innovation • New institutional logic • Reorientation in mindsets • Incumbents very challenged

Fig. 1 Type of change and challenges at the system level in relation to the four scenarios. *Note*: Adapted from Espegren et al. (2023) and Andersen et al. (2023b)

3.1 *Scenario Storylines*

3.1.1 Incremental Innovation Pathway (INC)

The INC pathway depicts a scenario with gradual system change following the current technological and socio-institutional patterns. This pathway is not associated with major leaps in the developments of prospective technologies and could be seen as a continuation of current climate and energy policies, with steady population growth as per current projections, and societal focus on economic growth.

Resources used for energy production include global oil and gas (O&G), renewable energy, and biomass. There is an increasing energy demand, but also increased energy efficiency. Transport demand increases, with a focus on electrification and biofuels. The decarbonization of industry will largely depend on energy efficiency measures and electrification, with existing incumbents in the energy and industry sectors maintaining a central role.

Despite increasing awareness, incentives for environmental behavior remain weak, and people largely stick to their current lifestyles in terms of consumption, travel, and energy use. There are potential controversies and conflicts related to land use, sustainability concerns, capital and technology participation, and distributional and recognitional justice.

3.1.2 Technological Substitution Pathway (TECH)

The TECH pathway is characterized by a sudden pressure for change at the broader societal level, leading to development and deployment of new core technologies, but less change in lifestyles. Moreover, population growth increases and the demands for energy and transport increase. Despite global O&G being used as feedstock for blue hydrogen production, renewable energy sources like floating offshore wind and biofuel production grow further. Alternative technologies and energy carriers like hydrogen, ammonia, batteries, and carbon capture and storage (CCS) become more available, opening routes for regionalization of existing industries.

Norway has niches in hydrogen, electrification, CCS, and hydrogen maritime technologies, providing an opportunity for the country to lead in these areas. However, potential social tensions, related to e.g., land use, sustainability contestation, and technology acceptance, may arise also in this scenario. Participation may also depend on capital and technology, raising issues of distributional and recognition justice.

3.1.3 Social Change Pathway (SOC)

The SOC pathway is associated with global conflict and unstable energy markets at the broader societal level and involves institutional changes reorienting from primarily economic growth towards sustainable well-being. There is a decrease in population growth due to less immigration. Due to social innovation and adoption of circular economy technologies and practices, more localized production networks and symbiotic innovations like automation become prevalent, reducing the demand for energy and global transport.

Core technologies are not replaced by new solutions to a large extent, hence emission reduction technologies such as energy efficiency, biofuels, battery-electric cars and vessels are implemented widely. Power generation experiences limited growth, and renewable energy and community-based solutions will be important. Existing incumbents in the industry face sharply increased CO_2 taxes and stronger disruptive policy measures than in INC and TECH.

The increased deployment of smart ICT-based solutions will be associated with energy use and lead to growth in e.g., data centers. However, Norwegian O&G production is expected to slow down and be shut down completely by 2034 due to climate concerns.

Potential Norwegian niches include smart transport solutions and digitalization. Circular bioeconomy innovation is also associated with green growth in some regions. The SOC pathway is characterized by increased environmental consciousness, leading to major changes in lifestyles, including less consumerism, less private ownership, more sharing and public services in transport, and a stronger focus on welfare and self-sufficiency.

3.1.4 Radical Transformation Pathway (RAD)

The RAD pathway is characterized by external shocks that trigger cascading disruption on multiple dimensions, involving major system change in both technological and social dimensions. The economy shifts its focus to sustainable development and well-being, with global collaboration expected to decrease and regionalization becoming more prominent. System reconfiguring innovations, such as circular economy, integrated and flexible power systems, and local production, are highlighted.

Like the TECH pathway, the RAD pathway sees a strong increase in maturity and availability of alternative technologies and carriers, such as floating offshore wind, hydrogen, ammonia, batteries, and CCS. This opens routes for regionalization of existing industry, including electrification, hydrogen, and CCS use. Advanced bioenergy/biofuel production based on Norwegian resources are also in place.

The primary energy supply will mainly consist of renewable energy, and O&G production is phased out by 2050. The demand for energy and food stabilizes 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. The road sector sees less transport, more shared electric vehicles, and increased use of public transport, bikes, and walking. Potential Norwegian niches in the Radical Transformation Pathway include renewable hydrogen, Industry 5.0, CCS, and smart & digital solutions.

3.2 Transition Bottlenecks

A central idea in combining techno-economic modelling with socio-technical analysis for assessing feasibility of scenarios is to identify ‘transition bottlenecks’, which are tensions between scenarios developed by models and current developments analyzed with a sociotechnical transition perspective (Geels et al. 2020; Wachsmuth et al. 2023). This analytical exercise provides a broader socio-technical check on the scenarios and allows to provide additional insights on the conditions for specific transition scenarios, and thus their feasibility. Turnheim and Nyqvist (2019) suggests four dimensions where the theoretical potentials revealed by modelling may collide with the dynamics of real-world systems.

First, *maturity of options* points to whether an innovation in question is developed-enough at a given time to be able to perform the role suggested by a modelled scenario. Different decarbonization technologies have different degrees of maturity (e.g., the maturity of LNG vs. relative immaturity of ammonia as alternative fuels in shipping). However, the pace of development of yet immature solutions is not pre-determined but rather dependent on the unfolding systemic processes, such as various actors’ continued efforts to explore cost-quality improvements, market formation, and availability of resources for further development of innovations (Hekkert et al. 2007).

Second, novel innovations must *fit with* the other *socio-technical systems and infrastructure* (for example, power grids, transport infrastructure such as roads and ports, etc.). Actors may have to either design innovations to fit with the existing systems and infrastructure, or the existing systems and infrastructure have to be fitted to innovations (Smith and Raven 2012; Bach et al. 2021), or more realistically, find a middle-ground between the two extremes. Such substantial change processes in large technical systems can be significant hurdles for innovation and time-demanding to carry out.

Third, innovations outlined by scenarios require *societal acceptability* to be adopted and to contribute to social sustainability. Acceptance may hinge on, e.g., the desirability of the modelled scenarios for the population, the perceived legitimacy of the actors pursuing the implementation of the scenarios, and the actual implementation of the scenarios (Turnheim and Nykvist 2019).

Fourth, fulfillment of scenarios may hinge on their *political feasibility*. This is related to, e.g., whether the kind of change in scenarios matches with the interests of powerful actors in politics, industry and civil society, and their vested interests (Normann 2015; Turnheim and Nykvist 2019).

3.3 Quantification of Socio-technical Transition Pathways

Based on the storylines provided in Sect. 3.1, key factors across each of the scenarios were mapped and parametrized as input assumptions in the energy system modelling analysis. The quantifications included technology specifications, limitations on energy production and transmission, energy demand developments per sector, availability of renewable fuels and end-use technologies, and varying investment costs corresponding to high or low technology learning rates.

An overview of the differences between the key assumptions in each scenario is provided in Fig. 2. For example, as mentioned in Sect. 3.1, lower technology learning is expected in INC and SOC and is portrayed with a lower bar, while high values are assigned to TECH and RAD since these pathways assume higher technology learning rates. These differences are further shown in the radar chart in Fig. 2 for other key input parameters, portraying the relative scale of the assumed values. In the case of hydrogen export, this is only seen under the TECH scenario which assumes that hydrogen export volumes are allowed, while the zero value in the other three scenarios denotes that no hydrogen exports are allowed. Further detail regarding the quantified values is provided in the NTRANS report (Espegren et al. 2023).

4 Results

This section describes the modelling results from the energy system and regional economic analysis applied to the scenarios priorly described in Sect. 3.

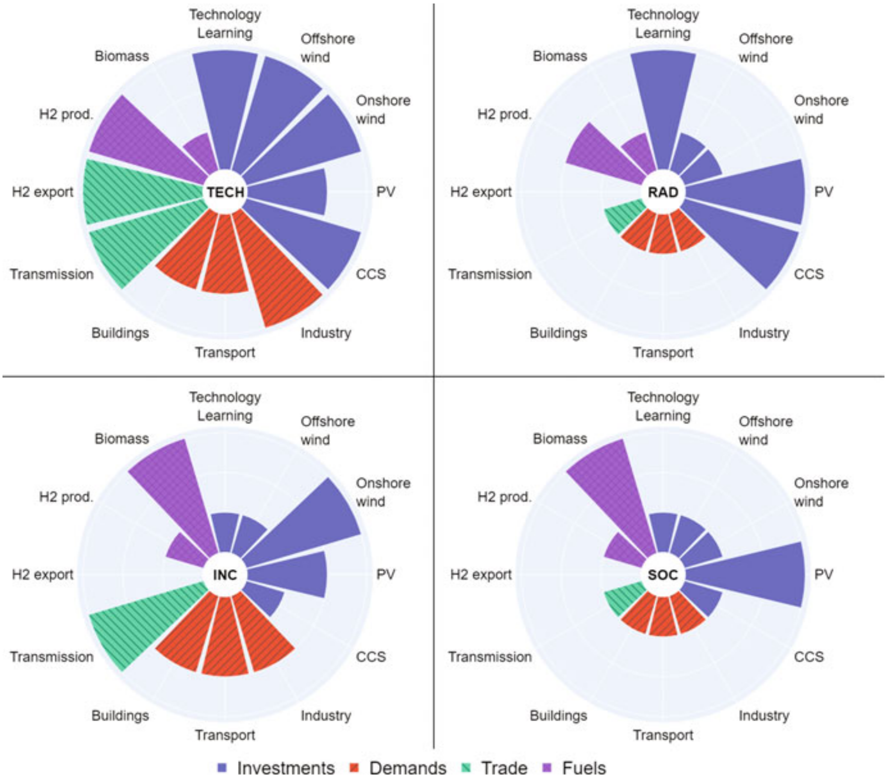


Fig. 2 Overview of differences between IFE-TIMES-Norway scenario assumptions. *Note*: The radar charts portray the varying levels relative to each of the key input assumptions in the scenario (i.e., low levels covering the innermost concentric axis, and high levels reaching the outermost concentric axis, and null values not displayed). The colors denote the inputs' category. Based on the 2050 quantifications from NTRANS (Espegren et al. 2023) (Color figure online)

4.1 Techno-Economic Analysis

4.1.1 Power Generation and Trade

The power generation mix in Norway for each of the modelled scenarios is presented in Fig. 3. In the scenarios where energy service demands are projected to increase (i.e., INC and TECH), there's a corresponding increase in total power generation. In these two scenarios, the onshore wind potentials (about 48 TWh) are fully utilized by 2050. Moreover, the increase in demand also drives up investments for other VRES, especially in the TECH scenario where electricity from offshore wind production covers the largest shares of the total power supply by 2050 (approximately 43%).

The generation mix sees increasing shares from offshore wind in both scenarios even though the two scenarios are characterized by contrasting technology learning

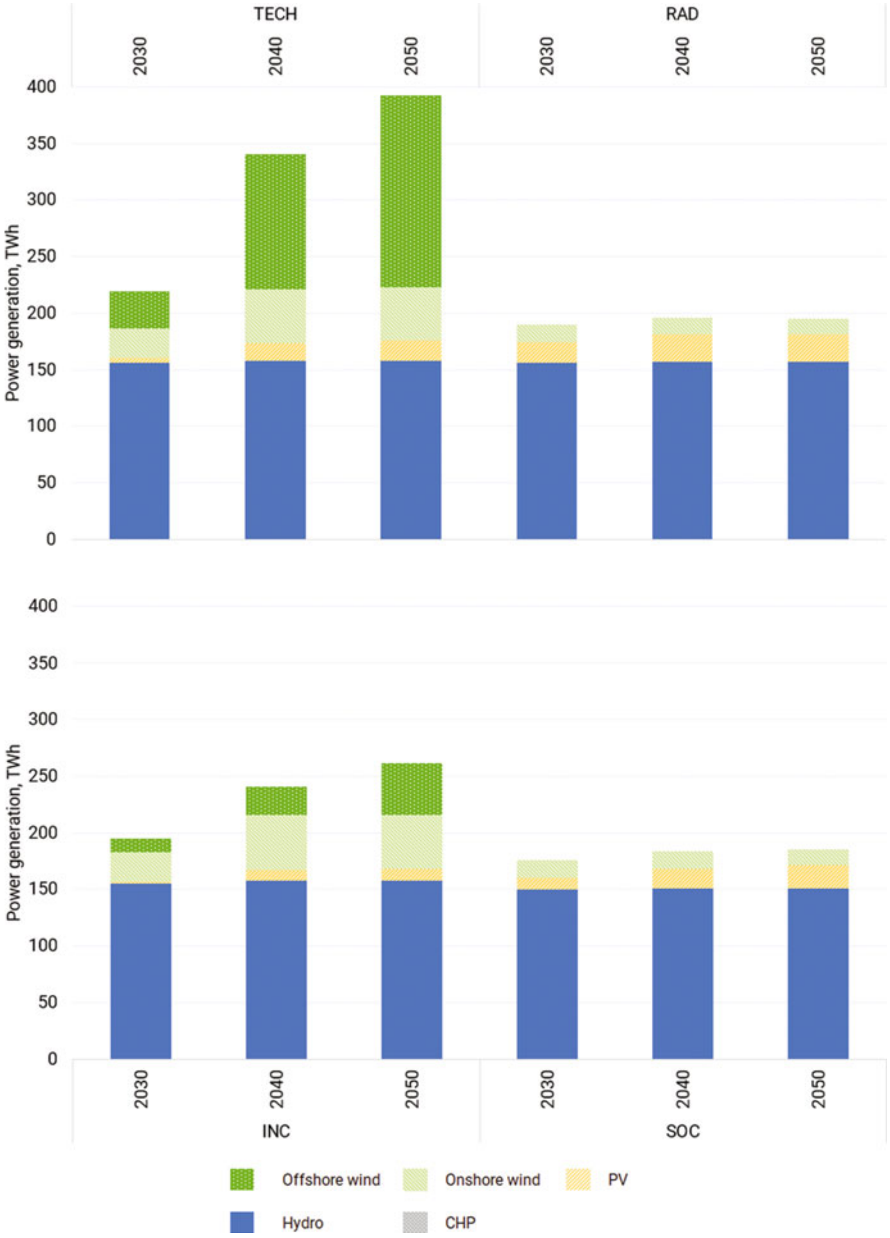


Fig. 3 Power generation (TWh/year) by technology for the four scenarios

rates to capture potential bottlenecks in technological development, with correspondingly higher investment cost assumptions in the INC scenario and lower costs in TECH. Due to common assumptions related to limited hydropower potential, the production volumes remain relatively constant across all four scenarios.

In contrast, the scenarios with low energy service demand—SOC and RAD—only see modest increases in the additional power generation required. In these scenarios, new production is expected mainly from PV applied in buildings covering about 11% of the supply mix by 2050, and only reinvestments in existing wind capacity. Offshore wind production does not play a significant role in the supply mix of either of these two scenarios, even in the case of the RAD scenario where high technology learning rates are assumed.

4.1.2 Transport Fuels

The energy consumption by carrier for the transport sector is presented in Fig. 4, showing the results for the four scenarios and two different CO_2 price assumptions. For all scenarios, a large share of the fuel consumption in 2030 consists of fossil fuels across different transport segments. In both the INC and SOC scenarios, fossil fuels are replaced mainly with biofuels by 2050, since no limitations in biofuel imports are considered in these two scenarios. The remainder of the transport sectors is decarbonized by electrifying the existing vehicle fleet. In TECH and RAD, electrification plays a larger role in replacing fossil fuel consumption with battery electric vehicles utilized when possible due to the high efficiency and technology learning. Meanwhile bioenergy is consumed as an intermediate replacement, showing less consumption by 2050 due to higher prices on biofuel imports. Emerging fuels like ammonia (NH_3) and hydrogen (H_2) also contribute to the sector's decarbonization, with increased uptake by 2050.

As seen in Fig. 4, imposing higher CO_2 prices accelerates the decarbonization of the sector. In the INC and SOC scenarios, this translates into earlier decarbonization achievable by 2040. Similarly, in the TECH and RAD scenarios, a faster uptake of carriers replacing fossil fuels is also projected, although a full decarbonization of the transport sector is not seen until 2050. Notably for both TECH and RAD, the high CO_2 prices enable a fully decarbonized transport sector, as opposed to the reference CO_2 price assumptions.

Given the dependency of biofuels in the INC and SOC, reaching a full decarbonization of the sector can be contingent to bioenergy availability and import prices as potential transition bottlenecks. As presented in Fig. 5, an increase of biofuel import prices comparable to the levels considered in the TECH and RAD scenario (i.e., an increase of 5 times relative to the reference value) limits the extent of the decarbonization even when considering the case of high CO_2 prices. Under a high biofuel price case, bioenergy replacements fall short while electrification and the use of hydrogen compensate as alternative fuel replacements.

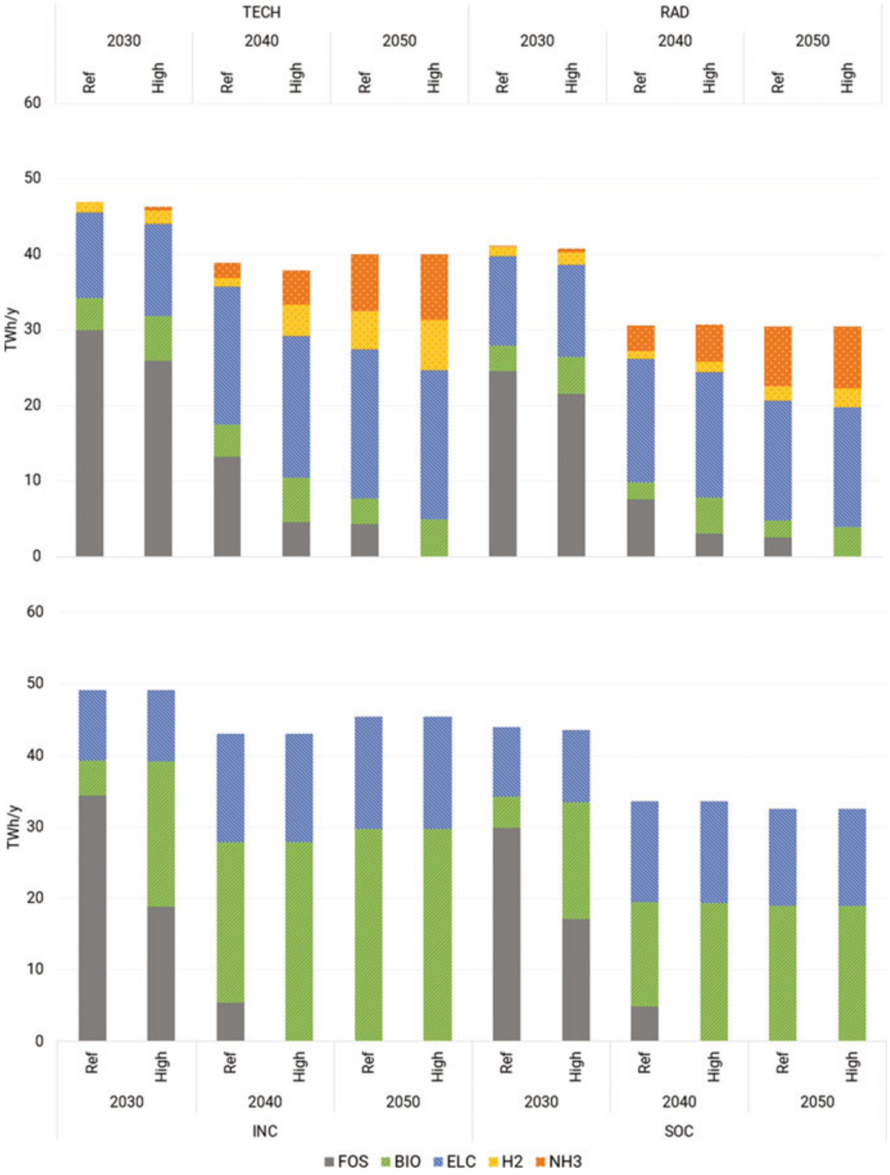


Fig. 4 Energy use in transport for the four scenarios considering different CO_2 prices (Reference -Ref- and a High CO_2 price). *Note*: It presents the values for fossil fuel (FOS), bioenergy (BIO), electricity (ELC), hydrogen (H_2) and ammonia consumption (NH_3)

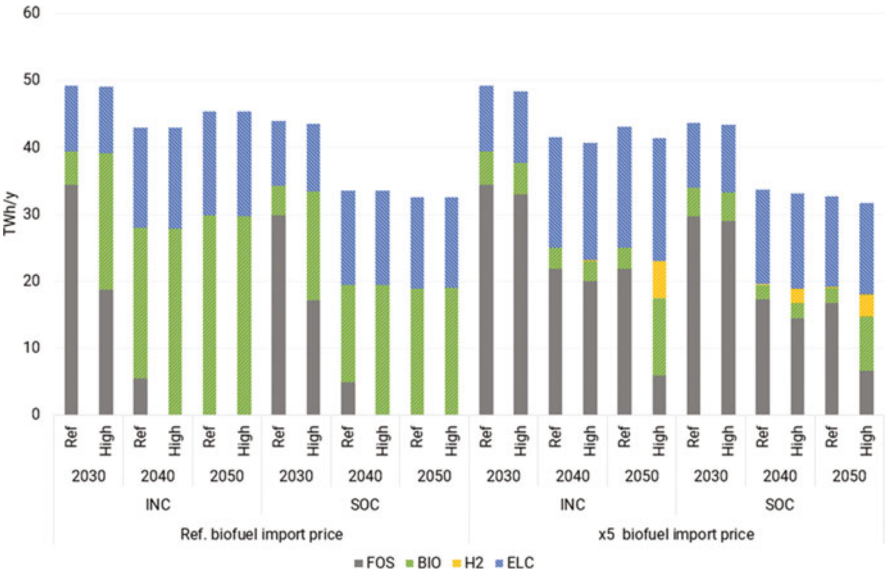


Fig. 5 Energy use in transport, considering different CO_2 prices (Ref. & High), and biofuel import prices

4.1.3 Hydrogen Supply

In the INC and SOC scenarios, hydrogen supplies about 5 TWh/year to cover demands in the industry sector with little change from 2030 to 2050. In contrast, the TECH and RAD scenarios see higher levels of hydrogen consumption—progressively increasing towards 2050—to cover end-use demands in industry and transport.

The TECH and RAD scenarios consider as base assumptions high levels of technology learning, which consequently contribute to a higher uptake of hydrogen utilization relative to the other scenarios due to lower investment costs in new capacity. However, bottlenecks in upscaling capacities and technological maturity might limit the uptake of hydrogen and new renewable capacity and are critical for these two scenarios. Therefore, lower technology learning (TL) rates—translating in higher investment costs—were considered as part of the sensitivity analysis. In Fig. 6, the results for the TECH and RAD scenarios are further explored.

Figure 6 shows how lower technology learning rates across the TECH and RAD scenario impact the production of both green and blue hydrogen, leading to lower overall hydrogen production levels. In 2050, this represents a reduction of about 34% and 9% for the TECH and RAD scenarios, respectively.

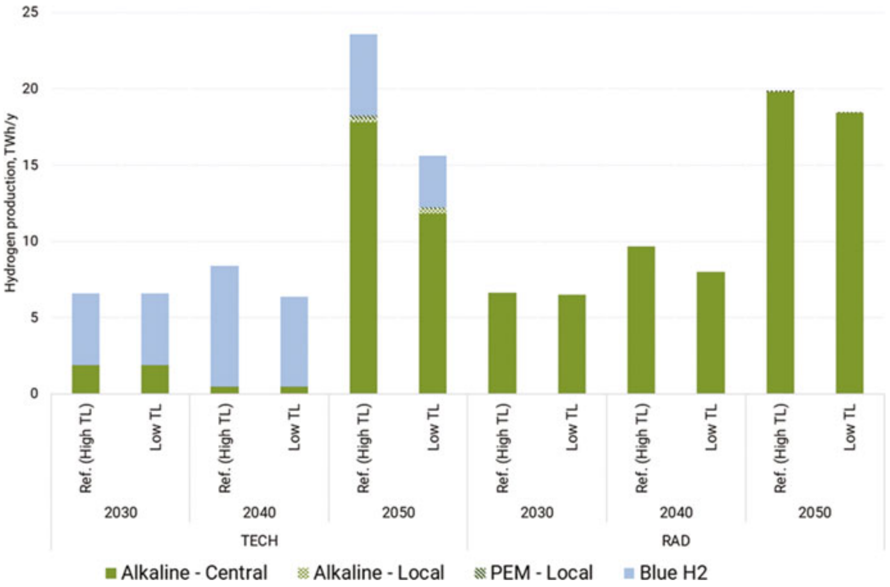


Fig. 6 Hydrogen supply by production technology from both central and local plants. *Note*: It includes alkaline and proton exchange membrane (PEM) electrolysis, and blue hydrogen from autothermal reforming (excluding Blue H_2 produced for export)

4.1.4 CO_2 Emissions

By 2050, all four scenarios present significant CO_2 emission reductions compared to 2018 (42.76 Mton/y), spanning a range of around 87–96% considering the respective reference assumptions for each scenario and CO_2 price assumption. As seen in Fig. 7, the industry sector has the highest emission contributions in 2050 for all scenarios, while only some emissions remain from district heating plants. For the TECH and RAD scenarios, which include larger CCS options and diverse green fuel replacements, the emissions from industry are decreased further than in the INC and SOC scenarios with less potential for industrial CCS or hydrogen.

The transport sector is fully decarbonized in the INC and SOC scenarios, due to unlimited use of bioenergy products at a moderate cost. Given the higher bioenergy costs in the TECH and RAD, the reference CO_2 cost applied in the scenarios is not sufficient to make it profitable to import bioenergy or achieve full replacement of fossil fuels with other technologies. Hence, emissions remain in the sea and air transport segments. However, when considering higher CO_2 prices, the decarbonization is accelerated across all scenarios. In the TECH and RAD scenario, additional levels of decarbonization are also unlocked leading to lower emissions in industry and driving further fuel replacements in sea and air transport towards a full decarbonization of the sector.

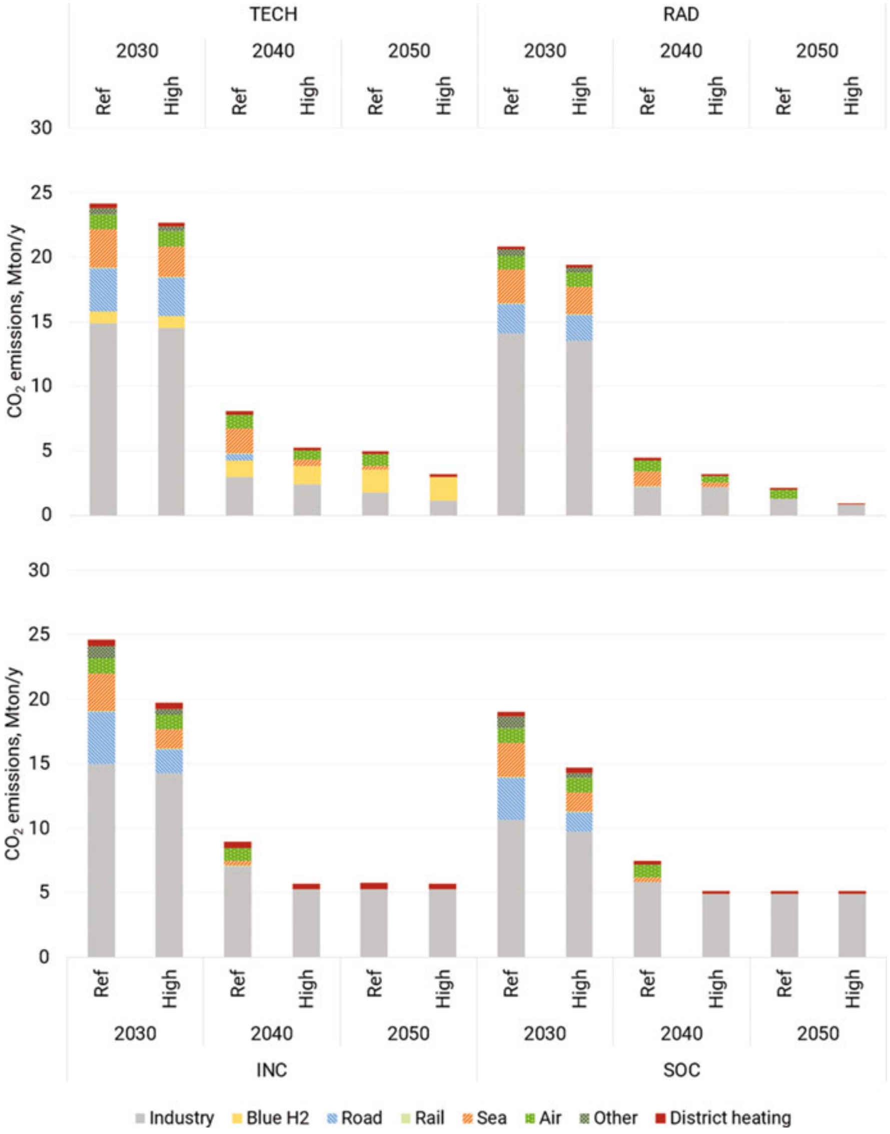


Fig. 7 CO_2 emissions by end-use for each scenario, considering different CO_2 price assumptions (Ref., & High CO_2 prices)

4.2 *Regional Economic Analysis*

The typical economic growth pattern of the NTRANS low carbon scenarios, as compared to a reference scenario, considers an initial decline in GDP growth due to

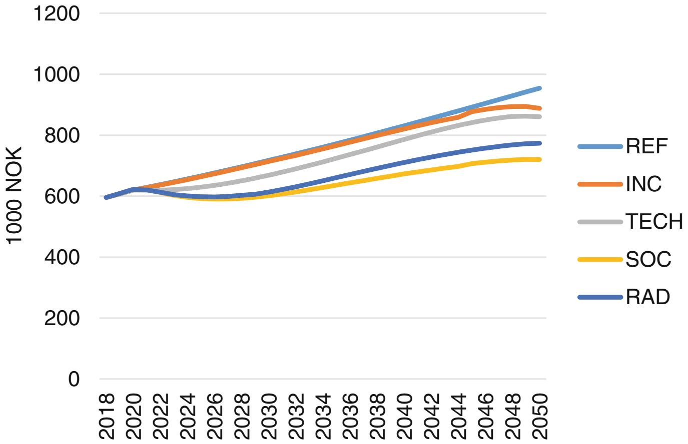


Fig. 8 Development of GDP per capita under the reference scenario and the alternative scenarios

the decline in value added for the O&G sectors, followed by a gradual improvement of the growth achieved due to the greater availability of capital, leading to large investments in industry and services. This is showcased in Fig. 8, as GDP per capita for all scenarios. The INC scenario mostly aligns to the reference scenario including continuous O&G extraction, presenting only marginally smaller differences. Economic growth decreases towards 2050 due to stricter decarbonization requirements and higher costs for sectors to reduce emissions.

The TECH scenario has a more pronounced decrease in O&G exports, with oil extraction decreasing by around 90% domestically and gas usage increasing in chemicals and blue hydrogen production. This faster phase-out leads to a greater decrease in GDP in the short run. However, due to improvements in industrial productivity, widespread adoption of hydrogen and the implementation of carbon capture and storage (CCS) in industry, the scenario aligns closer with the INC scenario.

In contrast, the SOC and RAD scenarios have a different economic focus based on societal change, and thus lower GDP levels compared to the Reference scenario. These two scenarios' weaker growth is primarily the result of lower labor productivity and a strong phase-out of O&G. Productivity loss under the RAD scenario is slightly mildened by the increase in industrial productivity and the use of CCS in industry.

The two largest contributors to the GDP are the industry and services segments (shown in Fig. 9). For industry, the construction sector represents its main value driver, performing particularly weakly under the SOC scenario. Growth in the construction sector slows due to reduced labor productivity, higher labor costs, and stagnant demand from a non-growing population leading to increased production costs and lower demand. Despite expensive labor and lower demand growth, the construction sector's reliance on less costly energy and materials allows it to expand,

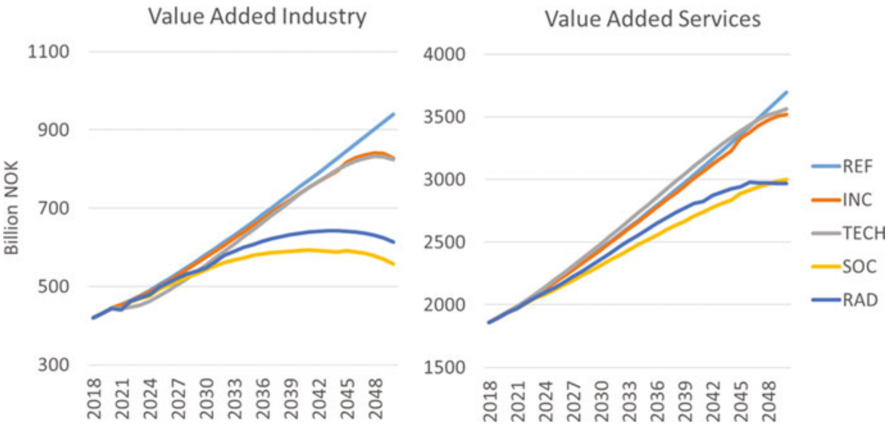


Fig. 9 Value added for the industry and service segments under the reference scenario and the alternative scenarios

albeit less than in the Reference scenario. Other industrial sectors, with a significant portion of costs tied to energy, face more substantial impacts due to decarbonization costs and rising wages on top of inherently declining demand. Notably, under SOC and RAD scenarios, the shift towards a circular economy model further reduces consumption. As a result, industrial value-added peaks around 2040, falling thereafter. Meanwhile, the INC and TECH scenarios, present a trend closer to the reference with a more moderate decline towards 2050.

The service segment's reaction to the changes in the SOC and RAD scenarios is less severe than that of industry. Within services sectors, the lower general economic growth decreases the speed of capital formation and investments in some sectors, like administrative services, by 2050. Lower economic activity under SOC and RAD leads to reduced labor demand compared to INC and TECH.

Under these scenarios, sectors capable of substituting labor for capital take advantage of lower wages to increase workforce and reduce capital dependence. Increased household consumption of services, driven by interest in a circular economy, softens the demand decrease due to the stagnating population and the general lack of focus on growth, allowing these sectors to maintain higher prices, albeit demand remains below the Reference scenario levels. In contrast, the TECH and INC scenarios, see an increased service production and labor demand.

In the majority of the sectors, the demand for labor under each scenario is anticipated to be lower than under the reference scenario (Fig. 10). When it comes to industries that make up the largest portion of employment and contribute significantly to overall growth, like industry or services, the TECH scenario manages to maintain an employment level that is comparable to the one in the Reference scenario.

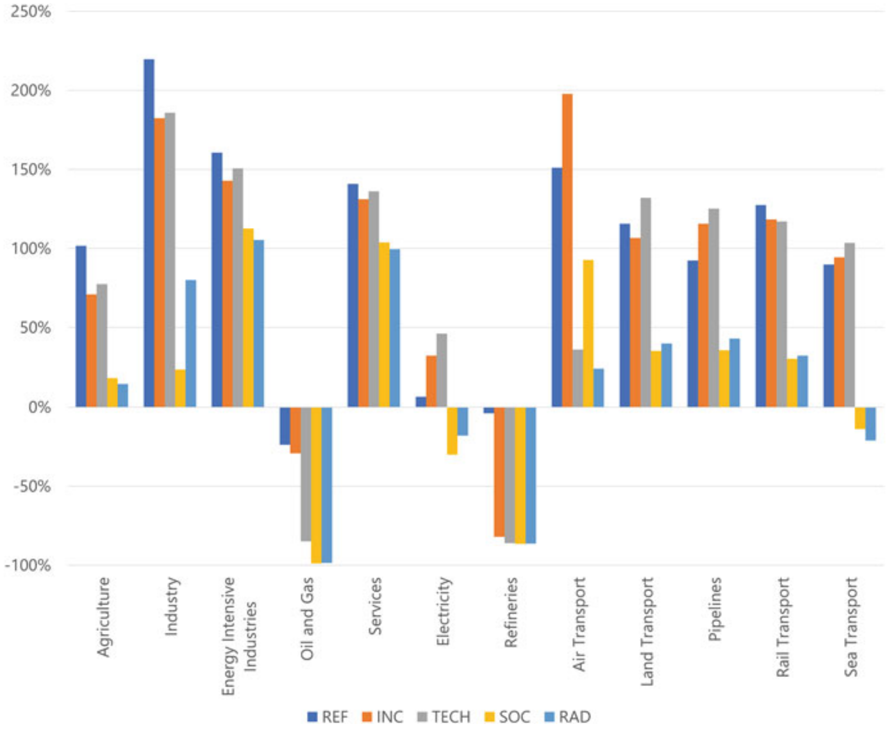


Fig. 10 Labor demand change compared to 2018 under the different scenarios

5 Discussion

The developments across the four scenarios facilitate different degrees of decarbonization towards 2050 in direct alignment with developing a clean energy system (SDG 7) and undertaking climate action (SDG 13). The scenarios, also portray the buildup of new infrastructure and emerging technical innovations (in line with SDG 9). As embodied by the RAD scenario, a combination of both major technological and socio-institutional change is required to enable the highest degrees of decarbonization and meet national targets (Regjeringen 2022b), i.e., 55% emission reductions by 2030 relative to 1990 levels (which are reported at around 51.5 million tons of CO_2). Enabling more ambitious reductions, as explored in the results, could require setting higher CO_2 prices, or other measures, to be well within said targets.

As mentioned, these reductions will also be conditioned by changes in behavior and lifestyle (aligned to responsible consumption, i.e., SDG 12), and emphasis on self-sustenance, circularity and local production and consumption (SDG 9). Intrinsically, the degree of change in those dimensions will yield different levels of economic growth and labor (SDG 8), as observed in the results of the economic analysis. Thus, the tradeoffs between prioritizing specific targets and development goals must be considered and put into perspective as part of the scenario analysis, which can then provide insight for distinct policy and societal preferences.

The scenarios may be slowed down by transition bottlenecks related to the crucial feasibility dimensions identified in Sect. 3.3: (1) the maturity of options, (2) system integration and infrastructure requirements, (3) societal acceptability, and (4) political feasibility (Turnheim and Nykvist 2019). The large-scale development of onshore and especially offshore wind in the TECH scenario is likely to meet challenges in terms of societal acceptance, related to "not in my backyard" (NIMBY) attitudes, competition with other marine activities such as fishing, shipping, leisure, and/or military activities. Although the need for a green transition may result in prioritization of windfarms, a legal solution for these tensions has not yet been found. Moreover, there may be potential conflicts with indigenous rights and the increasing focus on biodiversity and conservation in sustainable development policies. Distribution to shore and on land, as well as infrastructure for export, may also be associated with controversies.

Another issue in TECH, and to some extent in RAD scenario, is that some of the core solutions, such as hydrogen or floating offshore wind, are immature and the pace of their development is uncertain, due to yet underdeveloped industrial structures, technological knowledge, and institutions, e.g., in terms of regulations and cultural perceptions. This calls for adding time, cost and uncertainty while assessing the development and deployment of said technologies. This was captured in the techno-economic analysis, e.g., for hydrogen, by adapting the corresponding assumptions which yielded lower production volumes of blue and green hydrogen. Naturally, this has broader implications regarding potential exports and the need for diversifying the fuel supply with other alternatives like biofuels, electrification, or small shares of fossil fuels which themselves can be subject to additional constraints.

Likewise, the emergence of multiple, partly synergetic and partly competing solutions, creates uncertainty among actors, who fear lock-in to first generation technologies and in some cases postpone investment decisions in anticipation of stronger policy or market signals. In turn, uncertainty regarding supply and demand balance is associated with so-called chicken-or-the-egg dilemmas. Moreover, the development of necessary renewable energy infrastructure to power the production of alternative fuels may be considered as a transition bottleneck. Even though huge power grid investments are planned towards 2030 and measures to reduce the lead time have been proposed, it may take several years to get the capacity needed to electrify, set up, or expand alternative fuel production in a specific location. These factors may slow down transitions considerably. Similarly, Norway and Europe's reliance on import of critical raw materials required for the development and upscaling of new technologies should be considered and addressed, with a view to the current geo-political context.

A crucial bottleneck, especially for SOC, but also for the RAD scenario, is the lack of political will to shut down oil and gas in Norway. Contrary to the recommendation from a government-appointed climate committee (Klimautvalget 2023) the present government will not provide a closing strategy for the petroleum sector, but rather facilitate continued investments (Dagavisen 2023). Another critical factor (also relevant for the INC scenario) is the geo-spatial distribution and overall availability of biomass for energy. While multiple national initiatives to produce sustainable biofuels may reduce Norway's current biofuel imports, the costs are high; and, in a global long-term perspective, the demand for sustainable biomass is likely to exceed the supply (Kircher 2022). As explored in the techno-economic analysis, even higher costs, and limited availability of biofuels in INC and SOC, would imply relying on other alternatives such as electrification, hydrogen, but also hindering decarbonization efforts by extending fossil fuel use.

Meanwhile, both the SOC and RAD scenarios are dependent on significant demand reductions, linked to circularity, localization, and underlying lifestyle changes towards sufficiency. These may be politically difficult to foster actively unless strong grassroots movements and changes in public opinion form.

Despite shifts in technologies and changes in demand trends, all four scenarios show sustained levels of GDP and value-added growth as per the regional-economic analysis. However, higher levels of economic growth under certain scenarios, are not always aligned to higher degrees of decarbonization as illustrated by the RAD and SOC scenarios with contrasting metrics in these two dimensions. This highlights the need for developing transition pathways, that balance both ambitious decarbonization strategies and policy with economic growth for society.

While the scenario storylines include elements and quantifications specific to the Norwegian energy transition, the embedded considerations related to the degree of change and general challenges at the system level can be applied and contextualized to other areas. Meanwhile, analogous national modelling analyses can also be found in the ever-growing field of energy planning. Thus, the overall approach and methodology taken in the present study—linking socio-technical transition research in the scenario design with modelling analyses—could be replicated and adopted in other countries or regions.

6 Conclusion

This study presents an interdisciplinary approach to holistically analyze potential pathways for Norway's energy transition. The analyses link socio-technical transition research and modelling of the Norwegian energy system and the economy. These complementary perspectives provide valuable insight by capturing key considerations affecting the feasibility of the scenarios, and identifying critical issues that could slow down the transition towards a low-carbon future. Furthermore, the scenarios also illustrate that to reach ambitious levels of decarbonization across all sectors, a high degree of change will be needed in society and technological development, which will be accompanied by varying degrees of economic growth.

The energy system analysis shows that in the scenarios with minor socio-institutional change, where higher energy demands and electricity trade is expected, new additional renewable capacity will be needed for power generation despite potential bottlenecks affecting technology costs. However, the uptake of other new emerging technologies and fuel replacements (e.g., hydrogen, ammonia) across key sectors will be more likely when considering the scenarios with major technological change. On the other hand, minor technological change leads to decreasing but continued use of fossils and higher reliance on electrification and fuel replacements with biofuels. The role of these technologies and carriers will, however, be susceptible to the degree of technological maturity, resource availability, and policies in place.

Finally, the regional economic analysis shows that across all four scenarios—despite a slowdown compared to the reference case—economic growth can be expected. The growth in GDP and labor demand is closer to the reference in the cases with minor socio-institutional change, and lower in the scenarios with major change in this dimension. This illustrates a key tradeoff in the transition pathways, where higher degrees of decarbonization with sustainable energy sources can be realized, while balancing economic growth and societal development.

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