Energy Research & Social Science 112 (2024) 103496

Contents lists available at ScienceDirect

Energy Research & Social Science

journal homepage: www.elsevier.com/locate/erss

Original research article

Identifying and analysing important model assumptions: Combining techno-economic and political feasibility of deep decarbonisation pathways in Norway

Tor Håkon Jackson Inderberg [a], Hilde Andrea Nykamp [b,*], Ville Olkkonen [c], Eva Rosenberg [c], Karianne Krohn Taranger [a]

[a] Fridtjof Nansen Institute, Lysaker, Norway
[b] TIK: Centre for Technology, Innovation and Culture, University of Oslo, Norway
[c] Department of Energy Systems Analysis, Institute for Energy Technology, Kjeller, Norway

ARTICLE INFO

Keywords:
Political feasibility
Energy system modelling
Transition pathways
Decarbonisation
Transition policy
Sustainability transition

ABSTRACT

Understanding the political feasibility of transition pathways is a key issue in energy transitions. Policy changes are a significant source of uncertainty in energy system optimisation modelling. Energy system models are nevertheless continuously being updated to reflect policy signals as realistically as possible. Using the concept of *transition pathways* as a starting point, this cross-disciplinary study combines energy system optimization modelling with political feasibility of different transition pathways. This combination generates insights into key political decision points in the ongoing energy transition. Resting on actor support structure and political feasibility of four main pathway categories (electrification, hydrogen, biomass, and energy efficiency), we identify critical model assumptions that are politically significant and impact model outcome. Then, by replacing the critical assumptions with technical limitations we model a scenario that is unrestrained by assumptions about policy, we identify areas where political choices are key to model outcomes. The combination of actor preferences and modelled energy system consequences enables the identification of future key decision points. We find that there is considerable support for electrification as the main pathway to net-zero. The implications of widespread electrification, in terms of energy production and grid capacity, lead us to identify challenging policy decisions with implications for the energy transition.

1. Introduction

In the context of deep decarbonisation, an *energy system transition* is a change in the state of the whole energy system, as opposed to a change in individual energy technology or fuel source [1,2]. The concept of *transition pathways* in this article refers to the social and technological change process involved in moving from a high- to a low-carbon energy system. As there are various pathways to this outcome, what is seen as the ideal pathway — i.e. the combination of energy carriers, technical feasibility, existing infrastructure, and social changes — is often contested. Governments thus face the challenge of identifying and defining contested transition goals and devising policy instruments that enjoy sufficient political, technical, and economic feasibility to be implemented [3].

Energy system optimisation models are frequently used to support political decisions about transition pathways. Model scenarios identify economically optimal pathways given certain assumptions and boundary conditions [4,5]. In doing so, they make numerous assumptions about society, including political feasibility. Integration of institutional, political, and social factors is difficult to quantify and 'translate' to model input [6], and models have been criticised for lacking transparency about model structure and assumptions, and lack of credibility of those assumptions [7,8]. There is a risk that the modelled results might be 'feasible' in a techno-economic sense, but not in the 'real world' [9–12].

Assumptions about political feasibility may seem reasonable and are performed with increasing transparency in the modelling community, but their role is usually not discussed explicitly. Such assumptions include changes in political sentiments like support policies, licensing schemes, public acceptance of particular renewable technologies and

---

* Corresponding author.
E-mail address: h.a.nykamp@tik.uio.no (H.A. Nykamp).

https://doi.org/10.1016/j.erss.2024.103496
Received 1 September 2023; Received in revised form 15 January 2024; Accepted 23 February 2024

the like. Model results are thus shaped by the assumptions made about policy direction [13], and the results are used by policymakers and planners to support decisions about the energy system transition [14–17]. However, when the model output that is used to support policy decisions is based on assumptions about policy direction, model outputs risk becoming self-fulfilling - or to perpetuate path dependency of those decisions. Furthermore, if model assumptions are not explicitly discussed, policy-makers may view the results as 'truths' about the best path forward, without attention to the political choices that influence the model output [15].

Modellers are generally aware of the interface between models and policy-making [18] and addressing uncertainty has been identified as a key challenge in modelling [6,19]. As a result, modellers have tended to keep improving the models by working on the assumptions. However, increasing model complexity does not address problems of structural uncertainty [20,21]. Efforts to reduce uncertainty often include using larger and more complex models [22] and adding parameters (and assumptions) to the model — such as social aspects [23] policy [24,25], social acceptance issues [26], disruption and discontinuity [27], or roles of institutions and actors [28]. This, however, entails the risk of reducing politicised decisions to technical questions, thereby 'technicalising' contentious decision points that are ultimately political choices [29].

It is important to examine and discuss modelling practices and assumptions for energy transition pathways, because modelling often underpin both policy and business decisions. In this study, we explore links between energy system modelling and political analysis to identify key decision points – potential critical junctures – in an ongoing energy transition. Understanding the assumptions that lead to specific model outputs is fundamental if model results are to underpin implementable policy recommendations [6,16]. Therefore, our contribution examines and discusses the politically most relevant assumptions. Qualitative empirical analysis of existing pathway preferences enables us to identify key model assumptions that are based on existing policy or expectations about policy. Results from the qualitative mapping allowed us to experiment with the model parameters; by replacing model constraints based on policy assumptions with technical limitations, we identify key questions for policymakers that may be potential branching points in the energy transition.

We show how model assumptions link to important decision points of national decarbonisation pathways, with significant implications for the policies recommended by the model results, and potentially for the political feasibility of national decarbonisation pathways. We do this by *identifying the most important assumptions of energy system optimisation modelling and by analysing how these assumptions shape model outcomes and represent crucial political decisions for transition outcomes.*

Here we draw on the case of Norway's long-term energy system transition. A major reason for our choice is the position Norway has in decarbonising its primary energy production and use. The Norwegian land-based electricity system is 98 % renewable; the petroleum that is produced is mainly exported. The case of Norway offers insights for energy-carrier decarbonisation and electrification strategies also for other countries in Europe and elsewhere. In this area, there is often a significant gap between the techno-economic feasible options and the political feasibility of these same strategies. We examine some of the difficult political choices regarding political strategies and the choice of energy carriers to replace fossil fuels in sectors like industry, transport, and beyond.

2. Theory

Addressing a multi-disciplinary question about the political feasibility of transition pathways, we build on existing efforts to bridge transition studies, political science and formal modelling [30–34]. The following sections discuss the key concepts of transition *pathways* and the different types of *feasibility*.

2.1. Socio-technical and techno-economic pathways

In sustainability *transition studies* [35], the key object of study is the *process* of socio-technical system change, which is underpinned by a particular theory of change: Transition processes are conceptualised as the interplay between innovations struggling against stabilising forces [35,36]. These processes unfold at different speeds, in non-linear and path-dependent ways, or along different paths. [37,38]. Transition pathways are conceived as trajectories of development for a socio-technical system [39]. A socio-technical system gains momentum through path-dependency mechanisms created by forces such as vested interests and technological lock-in [40,41]. In terms of policy and governing, energy-system transitions policy can support technological niches and destabilise vested interests [42,43]. However, the scope for policy action is not constant: key decisions may change the direction or trajectory of the pathway. These are often referred to as 'windows of opportunity', 'critical junctures', or 'branching' points [39,44–48].

While transition studies tend to zoom in on the architecture of socio-technical pathways, techno-economic energy-system models on the other hand zoom out and depict the whole system including trade-offs and interactions. In modelling terms, a pathway is the cost-optimal mix of technologies, energy carriers and end-use over time, given a set of assumptions and targets [49]. Model-based studies can simulate or optimise energy system changes and emission targets to provide an overview of system interactions, trade-offs and overall pathway direction. As such, models show how decisions in one part of the energy system has consequences across it. However, models generate limited insights about the process itself, or on *how* to achieve the transition [9,50]. Implementing adjustments, such as support for a specific technology, is considered the task of policymakers. This brings us to the various concepts of *feasibility*.

2.2. Technical and economic feasibility

Energy system models indicate that it is technically feasible to reach net zero by mid-century [51]. *Technical feasibility* has been defined broadly as an alternative 'which does not contradict any known natural or technical law' [52] p. 260. Here, this can be understood as what is reasonably technically possible. In practice, technical feasibility assesses 'whether the new system can be developed and implemented using existing technology' Stefanou [53]. Examples may be found in the mapping of technical potential for wind power or roof-top solar for a country. The former will map the wind resources and the areas suitable for erecting turbines; solar mapping will start with mapping available building roofs with solar irradiation. Costs are generally not included in technical feasibility analyses.

Economic feasibility has been defined as the degree to which the economic advantages of something to be made, done, or achieved are greater than the economic costs [54] and is 'concerned with the availability and cost-effectiveness of resources needed to complete the project' [53] p. 332. Thus, economic feasibility relates to a cost-benefit analysis, to determine economically efficient development, and to which degree such factors represent constraints to the development of a technology [12,52]. These are often compared to alternatives and mapped through assumed (future) cost-curves. Examples are the Levelised Cost of Energy (LCOE) of various energy carriers, often with assumptions for future developments in cost reductions due to technology learning.

A model in its 'raw' form assumes perfect foresight and optimises the energy system from a social planning perspective [55]. Political feasibility is dealt with indirectly by modellers through assumptions about the demand for transport, heating, electricity etc. These assumptions are characterised by uncertainty because they depend on political choices, such as licensing schemes, subsidies, or restrictions. Feasibility is a measure of model validity that depends on the soundness of the assumptions [56]. Political feasibility is 'translated' to model input as restrictions limiting the technical or economic potential. Deliberations and decisions about how to do this are part of the 'craft' of modelling [55]. These decisions are sound (and necessary for models to work), but assumptions about political feasibility differ from technical and economic assumptions. Technical and economic assumptions are usually seen as more integral to the models. Despite possible weaknesses, they link clearly to the technical potential of technology while accounting for expectations relating to cost structures. As such, the models are usually seen as having their primary strengths in defining the technical and economic feasibility.

2.3. Political feasibility

Socio-technical transitions are often contested, and research on the *politics of transitions* has received increasing attention in recent years [57–59]. Broadly speaking, this line of research concerns conflicts and struggles over the pace and direction of transitions. Beyond the technical and economic feasibility included in the system models, a key area of contestation has been how the models deal with *long-term* pathway feasibility regarding other social factors, including acceptance issues, and the political propensity of a technology pathway over another.

These dimensions are inherently difficult to determine *ex-ante* and analyses will necessarily do so through significant simplifications. However, as shown by several studies [60–63], political intervention has been a crucial part of all major transitions, by inducing, shaping them, and has a role in managing the social consequences and pathway directions. A simplified political feasibility framework, therefore, is a natural approach for analysing these dimensions, which emphasises the long time-lines inherent in pathways approaches.

An outcome or policy is deemed politically feasible 'if there is an agent or group of agents who have the capacity to carry out a set of actions which will lead to that outcome or policy in a given context' p.2 [9,64–66]. Many factors will in reality influence the political feasibility of a pathway. These factors include ideology, political culture, societal paradigms, public sentiments, perceptions about fairness, institutions, polity, and interest structures. However, a key assumption here is that interest structures are one of the main influence factors behind the direction and shape of a transition pathway. While necessarily imperfect, this approach in combination with modelling, enables exploration of future key decision points, as the implications of the pathways can be illustrated more clearly. While refinement is needed in further research, this approach is a key contribution in the emerging field of analysing social factors with modelling.

The main reason for this choice is that interest structures influence how actors seek to modify public policies as well as other institutional structures such as technology standards, long-term visions, or societal values [67,68]. The interests of established incumbent actors are central in shaping transition directions at crucial decision points that may lead to very different ultimate pathways [39,45,69,70]. Such 'critical junctures' are key branching points [44,71–73]. We view policymakers as being embedded in society, and not as autonomous actors [74]. In turn, policymakers will usually propose or implement policy instruments that align with the interests of important stakeholders. While there is a difference between influential 'insider' industry interests and more peripheral 'outsider' groups [75], in cases where a pathway receives significant and tangible political and material support over time, there is likely to be positive feedback. Thus, investments in and ownership of established infrastructures, R&D, competence, and political alliances become stronger over time, partly through support by industry interests, and partly as new entrants adapt to the dominant structures and policy solutions [26,76–78].

While it is difficult to determine future interest coalitions, contemporary interest coalitions are likely to give some indications of future directions. Assuming that actors in a regime tend to shape policy according to their interests [79], we assume, *ceteris paribus*, that the future direction of pathways will follow the main structural and aggregated interest of the actors of relevance. This assumption is further strengthened by insights from path dependency theory, which argues that technical and economic structures tend to grow from earlier versions of a system [80]. Interests supporting or resisting change tend to be structured by these earlier versions of the systems through mechanisms that lead to a strengthening of the established 'path' [81]. These may be interrupted by 'branching points' or 'critical junctures', which may take the form of external system pressure or 'shocks' [44] that lead to political change and a new pathway [39,82]. These sets of interest structures are particularly relevant here, indicating that the dominant interest structures of the energy transition are likely to be generally stable. This adds robustness to analysing political feasibility through interest constellations. In addition, it supports analysing the most important politically influential assumptions in modelling, as these may lead to key decisions or critical junctures for the future energy transition pathway [31].

3. Research design and methods

In this study, we combine qualitative social science insights with energy system modelling through a dialogue-based bridging strategy [31,83]. In practice, that means we approach political feasibility from two perspectives and follow two methodologically distinct approaches. The one approach involves a theoretically informed, qualitative mapping of interest structures; the second is an assessment of model assumptions about political feasibility and modelling contrasting scenarios. Our research design consists of several steps, where insights from the qualitative mapping of political feasibility and model scenarios interact at strategic 'bridging points' and inform the next steps (see Fig. 1).

The first phase started with discussions about the key concepts shared between the fields – in particular, *transition pathways*, economic, technical, and political *feasibility* as well as the relative strengths and weaknesses of the different approaches.

In phase two, qualitative and quantitative research steps were conducted in parallel. On one hand we qualitatively mapped and analysed the political feasibility of different energy-carrier transition pathways in Norway (electrification, bioenergy, hydrogen, and energy efficiency). Here we drew on actor support and coding of consultation documents in a major public consultation of climate strategies in Norway held in 2020 (see Section 3.2 for details). A weakness of the approach is that the more influential actors are not distinguished from the more peripheral policy actors. While this is not directly accounted for in the public consultation coding, we discuss the implications of this choice in the discussion and suggest approaches to nuance actor influence. On the other hand, we explored ways to create a model scenario less influenced by assumptions about political feasibility. As a bridging point we collectively examined the full range of model assumptions, and found that the majority were politically inconsequential and, or only marginally affected model outcomes. This motivated the next step to identify the "critical assumptions".

Phase three constitutes a key bridging point where we selected the most critical assumptions. This was done through a series of meetings and group discussions. Selection rests on two key criteria: 1) those assumptions that are most technically significant in terms of energy carrier output, and 2) the most politically critical, i.e. those related to key political decision points. Key political decision points are typically those that are highly politicised – contentious or involving more than technical choices, like support schemes, certification, licensing schemes or similar, of societal importance. After identifying the critical assumptions, we started replacing assumed political restraints with technical limitations (see 4.2 and Table 3).

Next, in phase 4, we juxtapose and compare two model scenarios: a 'normal' model run that includes assumptions about political feasibility (see 3.1 for details), versus the 'reduced' scenario. The main difference here is that the most politically relevant assumptions of the model – like limits from the licensing scheme, restrictions of import of biofuels, and

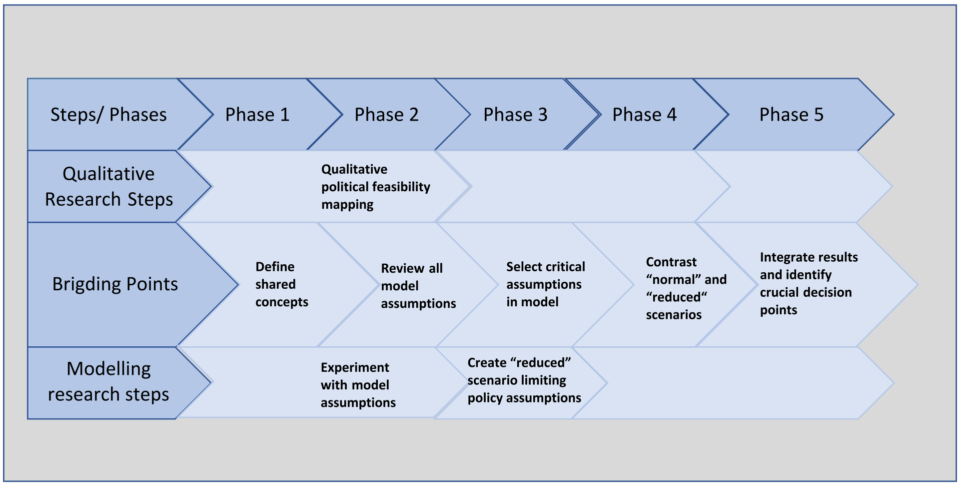

Fig. 1. Research process with steps and bridging points.

amount of roof-top solar – are excluded from the reduced model (see results in 4.2). Our aim here was to identify the main policy-relevant assumptions for further selection for the analysis.

Finally, in phase five, we use results from the political feasibility study and the contrasting model scenarios to analyse and discuss the selected critical assumptions. We assume that key political decisions that also significantly impact model output represent potentially *critical junctures*. Using empirical data on the political status in the field of Norwegian energy policy, we analyse model pathway output and identify and discuss the most significant political decisions likely to influence one pathway over another.

3.1. Description of energy system model design and assumptions

We performed energy system modelling using the IFE-TIMES-Norway model [84]. The model has been developed by the Institute for Energy Technology (IFE) in cooperation with the Norwegian Water Resources and Energy Directorate (NVE). A detailed documentation of the model is presented in [84]. This linear programming model for analysing the long-term development of the Norwegian energy system is generated by the TIMES (The Integrated MARKAL-EFOM System) modelling framework [85]. A simplified representation of the objective function of an inelastic and deterministic TIMES model and the constraints it is subject to are presented in Eqs. (1)–(3), where as a detailed mathematical description of the TIMES model is presented in [85].

$$\min_x c^T x \tag{1}$$

$$subject\ to \sum_k A_{k,i}(t) \geq D_i(t), ; i = 1, \ldots, I; t = 1, \ldots, T \tag{2}$$

$$and\ Bx \geq b. \tag{3}$$

In (1), the model minimises the total discounted cost of an energy system over decision variables $\boldsymbol{c^T x}$ to meet the demand of energy services for the regions over the period analysed. Total energy system cost vector $\boldsymbol{c^T}$ includes investment costs in both supply and demand technologies, operation and maintenance costs, and income/cost from electricity export/import to/from regions outside Norway. Further, the minimisation problem is subject to a series of constraints. In (2), $A_{k,i}(t)$ is the supply of energy from various end-use technologies (k), which must be greater than or equal to the demand $D_i(t)$. Here the IFE-TIMES-Norway model offers a detailed description of end-use energy; and the demand for energy services is divided into several end-use categories within industry, buildings, and transport sectors. Demand can be met by both existing and new technologies using energy carriers such as electricity, district heating, bioenergy, hydrogen, and fossil fuels. Consequently, the use of energy carriers is a model output and not a model input, hence making the sector coupling a part of the optimisation problem. Other input data include fuel and carbon prices, exogenous electricity prices in regions outside Norway,[1] renewable energy resources, and technology characteristics such as capital and operational expenditures, efficiencies, technical lifetime, and learning curves.

In (3), the term $Bx \geq b$ corresponds to all other TIMES constraints: the maximum installed capacity of a technology, minimum share of a technology, etc. In terms of renewable energy sources (RES), the model differentiates between run-off-river and reservoir hydropower plants, onshore and offshore wind power, as well as roof-mounted (or building-applied) photovoltaics (PV). For new investments, various technology options are available, involving differing costs, operational conditions, and technical potentials for each bidding zone. Existing transmission capacity, within Norway and to neighbouring regions, is modelled exogenously and is based on the current transmission capacities (TC) and ongoing capacity expansion. The model allows for new investment to TC, both on existing and new connections. The first year of investment is fixed to the year 2030 due to the long lead-time of new transmission line projects. Electricity spot-prices in the bidding zones in Norway are endogenous, as those are the dual values of the electricity balance equation. The IFE-TIMES-Norway model has been soft-linked to various European power system models, such as the EMPIRE model [86], to capture the characteristics of the European power market under different future pathway scenarios. Spatially, the IFE-TIMES-Norway model covers the five geographical bidding zones for electricity price setting in Norway. The model provides strategic investment (long-term) and operational (short-term) decisions for model periods starting from 2018 to 2050. Furthermore, a model period is divided into 96 sub-annual time slices. In this case, these time slices represent the four meteorological seasons (winter, spring, summer and autumn) that are represented by representative days consisting of 24 chronological hours.

3.2. Coding of data from the public consultation

In operationalising political feasibility as actor support, the national consultation *Klimakur* ('Climate Cure') held on 30 April 2020 is helpful for identifying actor interests and contestation points. *Klimakur* is a general plan for nationwide emissions abatement in Norway. It includes 60 measures in various areas of the economy, which is expected to

---

[1] Countries with significant transmission line capacities to/from Norway are Denmark, Sweden, Finland, United Kingdom, Netherlands, and Germany.

reduce Norway's emissions by 50 % by 2030. It includes numerous measures within sectors ranging from road transportation to agriculture and the construction sector; total electrification (assuming all measures are implemented) is projected to contribute to 13.6 mill tons CO_2-eq in the period 2021–2030. *Klimakur* received 1730 submissions: 51 from municipalities and counties, 190 from organisations, private and public companies, and 1489 from private individuals. All individual submissions are publicly available, including the Environment Agency's summary in a separate report. *Klimakur* serves as our empirical basis for analysing the feasibility of Norwegian transition pathways, complemented supplementary documents.

By excluding private individuals, levels of government, and political parties, we focus on the core stakeholders, assuming that these have key interests and expertise. Of the core stakeholders in this group, 190 submissions remained in the initial pool. We then excluded those not registered with an organisation number, those that represented a political party, or represented regional branches of national organisations. The excluded entities have their own political channels through elections (individuals) or by being part of a polity and governance structure. Applying the selection criteria to the selection pool, we chose the consultation responses of 139 actors for analysis.

To map actor interest structures and arguments concerning the support and devaluation of the different pathway choices, a text analysis of the consultation responses was undertaken, using the qualitative data analysis software NVivo. This approach involved the coding/categorisation of sections of text into relevant categories, enabling us to identify, support and criticism of different pathway scenarios efficiently and in a structured way.

The process of coding the consultation submissions involved a mix of deductive and inductive iterations. First, we developed a coding scheme with an initial set of categories. This was based on an examination of key recent policy documents – energy White Papers, official reports, and key actors' reports. This led to four main pathway categories (electrification, hydrogen, biomass, and energy efficiency), and several sub-categories representing various sectors within each pathway. Further, specific political instruments either advocated for or criticised by actors were also used as a category within each main and sub-category. Second, during the analysis, new categories were inductively created based on new findings that emerged from the pre-developed coding scheme. The analysis was then conducted by taking the basis of these categories and coding various statements from the consultation documents as references to the specific pathway categories in NVivo. Such statements disclosed the actor's opinion of a specific pathway. In total, 848 statements from the various actors have been coded to the different pathways. Additional sub-categories were used to contextualise the findings. (See the full coding scheme in Appendix A: *Klimakur* coding scheme.) Finally, on the basis of sector representation and coded statements, we clustered the actors based on similarities in pathway support, to obtain a more aggregated picture of actor pathway preferences. This aggregation indirectly indicates cluster dominance and support for one pathway over others; in the context of this study, we interpret this as representing the political feasibility to be used with the modelling.

For the analysis, a greater number of actors' support and coalition for the pathways was used to represent higher political feasibility for one pathway over another. This was in turn used to identify concrete assumptions in the modelling, for further identification and discussion of pathway modelling and political branching points.

4. Political feasibility scenarios

4.1. Findings from mapping the political feasibility of pathways

Our analysis of 139 actors' consultation responses to *Klimakur 2030* identifies statements of support for all four pathways – electrification, bioenergy, hydrogen and energy efficiency (see Table 1). The pathway that received the greatest actor support was the *electrification pathway,* in which 77 actors mentioned the necessity for continuous electrification of several sectors, such as agriculture, construction, district heating, heavy industry, offshore petroleum extraction, and transport. The second largest category was the *bioenergy pathway,* with 63 actors favouring bioenergy as an element in Norway's decarbonisation strategy. The sectors mentioned here were agriculture, construction, district heating, industry and transport sector. Further, the *energy efficiency pathway* was supported by 34 actors, who noted energy efficiency measures to be applied to buildings and construction, industry and transport sectors. Also, the *hydrogen pathway* received significantly lower actor support than the electrification and bioenergy pathway: only 32 actors expressed support for promoting the use of hydrogen in the construction, industry and transport sectors. Here it should be mentioned that also statements criticising all four pathways occurred in the consultation responses: these are not assessed here, as we operationalise political feasibility only as actor support.

Table 1
Support for the different pathways.

Type of pathway (main categories)	Number of actors
PW1 Electrification	77 (55%*)
PW2 Hydrogen	32 (23 %)
PW3 Bioenergy	63 (45 %)
PW4 Energy efficiency	34 (24 %)

* Percentage of total actors (139).

If the political feasibility of a pathway is understood solely in terms of the number of actors supporting it, electrification emerges as the most politically feasible pathway in Norway. This is followed by the bioenergy pathway and the hydrogen pathway. There is support for energy efficiency, but energy efficiency entails a different logic, as it is not an energy carrier in its own right; moreover, it is generally seen as support for the three other pathways. See Table 1 for a crude ranking of the overarching political feasibility of the different pathways.

Based on the data from the NVivo analysis, we have further clustered different types of actors into actor groups (clusters) to shed light on the aggregated support for the main pathways categories within these coalitions. Such support is considered as a policy preference. As can be seen in Table 2, there are various actor types within each cluster, making the clusters quite heterogeneous. Cluster 1 includes most of the private companies and no research organisations, whereas Cluster 2 has no private companies. The full list of actors within each cluster can be found in Appendix B: Overview of actors selected for the consultation analysis and in the cluster analysis.

Within each cluster, all four different pathway preferences are present, in different balances for each cluster (see Fig. 2). This indicates that actors' policy preferences are quite complementary. However, although all four pathways are present in all clusters, they differ in the degree to which they are represented. This means that there is a division among the clusters' policy preferences. Electrification is the dominant policy preference in Cluster 1. In Cluster 2, hydrogen is most emphasised; Cluster 3 is dominated by bioenergy policy preferences. It can be

Table 2
Overview of actor types within each actor cluster (group of actors who share similar policy preferences).

Type of actors	Cluster 1	Cluster 2	Cluster 3	No cluster affiliation
Interest organisation	29	3	24	15
Private company	11	0	4	6
Public company	4	2	3	1
NGO	5	2	7	6
Research organisation	0	1	2	7
Government agency	2	1	0	3
Intergovernmental organisation	0	0	0	1
Total	51	9	40	39

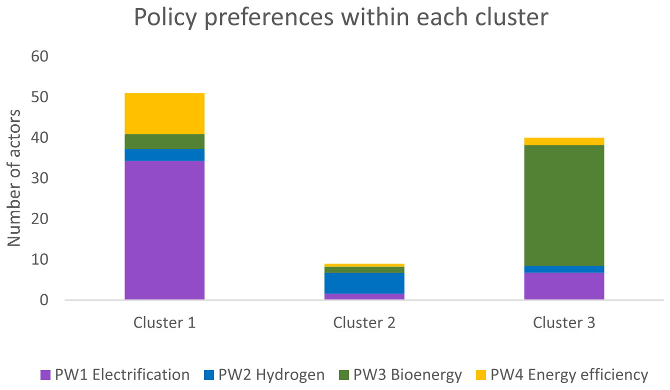

Fig. 2. Policy preferences within each cluster.

assumed that the specific actors within each cluster can be seen as strong supporters of the dominant pathway in the clusters to which they belong.

4.2. *Comparing model scenarios*

From the pathway preferences identified above we review assumptions in the reference scenario (Section 4.2.1) and create a 'reduced' scenario where we remove the key assumptions about political feasibility. Juxtaposing the two scenarios makes clear the role of political feasibility assumptions and how they represent contested political choices and debates.

4.2.1. *Reference scenario*

Our reference scenario is based on a basic version of the IFE-TIMES-Norway model. The main assumptions behind the reference scenario are presented below; a detailed description of the IFE-TIMES-Norway model is presented in [84]. Analyses are normally done with different assumptions, including political feasibility, but not necessarily with explicit political discussions. Our model is driven by exogenous energy service demand projections for industry, buildings, and transport sectors. The development of energy service demand in different sectors is presented in Fig. 3, and is described in more detail in [84]. Demand for energy services in the industry sector is assumed to increase by around 47 % by 2050, due mainly to new industry activities (e.g., battery production plants) The demand for residential and non-residential buildings is assumed to increase by around 7 % and 4 % by 2050, respectively. The projection of transport sector demand is based on the National Transport Plan [87]; road transport energy demand is assumed to increase by 37 % by 2050, whereas only a modest increase of 14 % is assumed for the other transport modes (e.g., air, maritime, rail).

End-use demand is affected by the improved energy efficiency of end-use technologies, mainly heat pumps and more efficient vehicles. The limits on the utilisation of these end-use technologies in different sectors are described in detail in [84]. The adoption of end-use technologies, especially energy efficiency and zero-emission solutions, is further affected by various exogenous economic assumptions. The CO_2 emission price[2] in Norway is expected to increase from 60 €/tCO_2 in 2020 to 455 €/tCO_2 by 2050. Energy use-related CO_2 emissions are not capped in the model. Taxes and subsidies are assumed to remain constant at current (2023) levels. A grid fee is applied for end-users and is kept constant during the modelling horizon 2018–2050. Our assumptions regarding exogenous electricity prices in regions outside Norway are based on the NVE's long-term power market analysis [88].

The Norwegian electricity system is dominated by hydropower. In 2020, Norway had a total electricity generation of 154 TWh, of which 92 % was from hydropower, 6 % from onshore wind, and around 2 % from thermal power [89]. The system is interconnected to the neighbouring countries via transmission lines, with a total capacity being around 8 GW in 2020. Historically, Norway has been a net exporter of electricity, with exports typically around 15–20 TWh [89].

The new generation capacity is based on renewable energy sources. The hydropower potential has a potential to increase due to the refurbishment and expansion of existing capacity and investments in new capacity [90]. The electricity generation from hydropower has the potential to increase to 157 TWh in a normal year. The potential for onshore wind power generation is 48 TWh per year, of which 15 TWh is from existing plants, 11 TWh is based on the applications for wind power concessions [91] and 22 TWh is estimated additional potential. Offshore wind power potential is only 35 TWh, according to estimates provided [92]. The building-applied solar PV potential is estimated available roof areas of existing and new buildings, taking into consideration the restrictions due to shadows, other use of roof areas, azimuth etc. Thus, the total potential for solar PV is assumed to be 24 TWh per year. The expansion of transmission line capacities within Norway and neighbouring countries is limited to 2 GW and 19 GW, respectively. Additionally, offshore wind power plants can be connected to 18 GW transmission capacity by 2030, increasing to 36 GW in 2050.

Bioenergy can be used as primary energy to produce heat (e.g., biomass-fired boilers), as a transportation fuel (e.g., biogas as vehicle fuel), or as a raw material for domestic production of pellets/chips, bio coal, and biofuels. Biomass can also be used as raw material in the industry sector. The reference scenario assumes that Norway will become self-sufficient in bioenergy, interpreted as net zero import of bioenergy by 2035. The potential for biomass resources is estimated to be 31 TWh per year by 2030 in Norway, based on sustainable timber-felling. The potential for domestic biogas production in Norway is assumed to be 2.7 TWh per year, and the potential for municipal waste is assumed to remain constant at the current level of 3.9 TWh per year.

Domestic green hydrogen production and consumption are relevant here. The green hydrogen produced in the electrolysis process can be stored and/or delivered for use in industrial and transport sectors (road, maritime).

4.2.2. *Reduced scenario*

Our 'reduced' scenario operates with limited assumptions about the political feasibility of the expansion of renewable energy resources, transmission capacities, and domestic consumption of bioenergy resources. We exclude limitations based on assumptions about policy and focus on the technical potential. For example, the upper limit for solar PV is based on area requirements and power density of solar PV systems as estimated in Bogdanov et al. (2019) [93]. The technical potentials for onshore and offshore wind are based on estimates by the European Environment Agency [94]. The technical potential for onshore wind power is estimated on the basis of the power density of wind turbines and available land cover, and offshore wind technical potential is estimated on the basis of available areas of water for offshore wind installations within national jurisdiction. The expansion of Norway's hydropower resources is excluded, as the development of this renewable resource is to a large part restricted by the Protection Plan for Watercourses [95]. Therefore, we assume that the technical hydropower potential will remain at the same level as described in the reference scenario. The scenario assumptions are summarised in Table 3. The technical potentials are combined with technology-specific capital and operational expenditure – difficult when the potential is almost infinite. Here, we have simply assumed the highest cost class (when available) for the increased technical potential.

The effects on domestic hydrogen production and consumption are analysed indirectly. Here we assume that national policies do not impose technical limitations on the demand-side technologies: instead, shifting market conditions (e.g., changes in the Norwegian energy generation

---

[2] Monetary values are presented in euro (€) using exchange rate of 9.6 NOK/€.

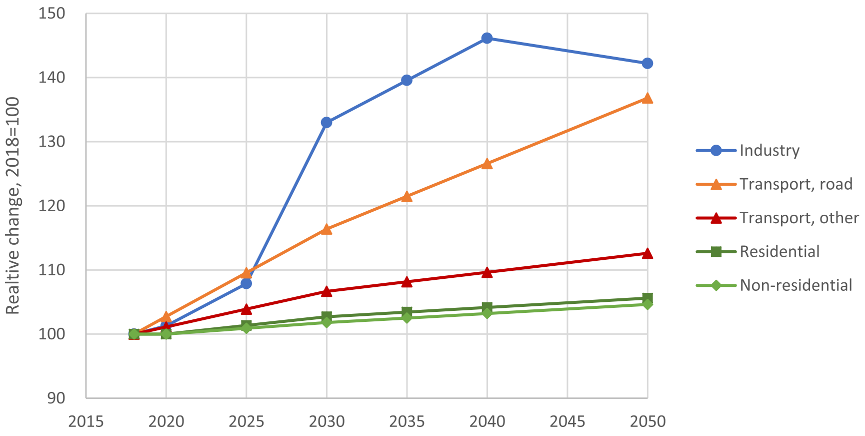

Fig. 3. Development of energy service demand in the industry, buildings, and transport sectors. The change in demand is presented as a relative change (2018 = 100).

mix) can affect the techno-economic feasibility of these technologies.

5. Modelling results

In the following, we present the results of the ‘reduced’ techno-economic model. We take the reference scenario results as a starting point and then exclude the critical scenario assumptions (identified in Table 3) one by one. This breaks with the standard modelling tradition of working to increase ‘realistic’ model results and leads to some arbitrary results, but these results are important for identifying the political choices (excluding economic and technical questions) of decarbonisation processes with the greatest influence on national decarbonisation pathways.

5.1. *Electricity supply*

Against the background of electrification as the main national strategy (see Section 4.1), Fig. 4 shows the modelling results when critical assumptions relating to the diffusion of the main production technologies are included in the reference scenario. In the reference scenario, hydropower continues to be the dominant electricity supply source in Norway until 2050, with an annual generation of ca. 155 TWh. Onshore wind power generation is expected to increase gradually from 23 TWh in 2030 to 44 TWh in 2050, and solar PV generation is expected to increase from 6 TWh in 2030 to 23 TWh in 2050. Offshore wind generation starts to increase in 2040, remaining at a constant level of 15 TWh until 2050.

The identified assumptions related to onshore and offshore wind have the greatest effect on the development of the Norwegian electricity generation mix. When the political factors related to onshore wind are excluded (Sce4), onshore wind power generation will rise as the major source of electricity by 2035. The same can be observed with offshore wind power (Sce3), which, however, will surpass hydropower as the main generation source in 2050. The critical scenario assumption related to solar PV does not significantly affect the development of the Norwegian electricity generation mix. Moreover, with high penetration of onshore wind power, a ‘cannibalisation’ effect can be observed between onshore wind and solar PV.

5.2. *Electricity trade and grid development*

Fig. 5 presents the modelling results regarding electricity trade between bidding areas in Norway and Europe. In the reference scenario, greater electricity consumption in Norway will increase the need for electricity imports from Europe. Increasing the share of variable renewable energy will also require balancing via interconnectors, which can be observed as increasing electricity exports. The critical scenario assumptions regarding onshore and offshore wind power show that the expansion of wind resources can be closely connected to increasing electricity exports. This can also be seen to increase the domestic electricity trade[3] within Norway, which will require major domestic grid upgrades and expansion.

5.3. *Bioenergy consumption*

Fig. 6 presents our modelling results regarding the consumption of bioenergy resources in Norway until 2050. In the reference scenario, the consumption of bioenergy increases by 32 % between 2018 and 2030 and remains at a relatively constant level until 2050. This is based mainly on biomass use for production of heat in district heating plants, industry, and buildings. Biofuel is used as a transition fuel in the transport sector. The use of biofuel starts to decline already before 2030 as it is replaced by electricity consumption, mainly battery-electric vehicles. The critical scenario assumptions regarding the supply of bioenergy resources are observed to mainly affect the use biocoal, and it is observed to be connected to the availability of domestic biomass that can be used to produce biocoal. In this regard, the use of biocoal starts to increase in 2040 when it is used to substitute fossil coal in metal reduction processes.

5.4. *Hydrogen consumption*

Fig. 7 presents the modelling results regarding the domestic supply of hydrogen and consumption in Norway's industry and transport sectors until 2050. In the reference scenario, national hydrogen consumption will be relatively low in 2030, increasing significantly by 2050. The industry sector stands out as the largest user of hydrogen in Norway in the mid-term; however, it will be surpassed by the transport sector by 2050. Especially, the consumption of ammonia in marine transportation is expected to increase significantly, to approx. 9 TWh by 2050. A total of around 23 TWh of hydrogen is forecast for domestic use in Norway by 2050. Excluding policy assumptions regarding capacity expansion in the reduced scenarios does not appear to have a significant impact on domestic hydrogen production and consumption in Norway during the modelling horizon. In mid-term, however, high availability of onshore windpower (scen 4) generation in combination with transmission grid expansion (scen 6) are observed to increase the feasibility of domestic

---

[3] Domestic trade is calculated from hourly level power flows between bidding areas or offshore wind power regions to the connected bidding areas, which are summed to an annual level.

Table 3
Comparing selected assumptions in reference and reduced scenario.

		Reference scenario	Reduced scenario
Electricity supply	Onshore wind	Upper limit for onshore wind is based on the concession system 48 TWh (incl. existing capacity)	Upper limit is increased based on the unconstrained technical potential to 2300 TWh (Sce4)
	Offshore wind	Upper limit for offshore wind is based on estimates provided in the offshore wind impact assessment report is 35 TWh	Upper limit is increased based on the unconstrained technical potential to 2200 TWh (Sce3)
	Solar PV	Upper limit for building-applied solar PV (e.g., roof-mounted) is 24 TWh	Upper limit is increased based on the technical potential to 1250 TWh[1] (Sce5)
Transmission	Trans-mission lines, domestic	Upper limit for transmission line capacity expansion is 2040 MW; first year of investment is 2030	Upper limit is removed from 2030 and onward (Sce1)
	Trans-mission lines, inter-national	Upper limit for capacity expansion is 12,900 MW; first year of investment is 2030	Upper limit is removed from 2030 and onward (Sce2)
	Trans-mission lines, off-shore wind connected	Based on offshore renewable energy projects, both to Norway and international trade	Upper limit is removed from 2030 and onward (Sce1, Sce2)[2]
Bioenergy resources	Biofuels	Upper limit for imported biofuels is 7 TWh (0 TWh from 2035)	Upper limit for imported biofuels is removed (Sce8)
	Biomass	Upper limit for domestic forest harvesting for logs and biomass is 16 TWh (31 TWh in 2030)	Upper limit is removed from 2030 and onward (Sce10)
	Biocoal	Upper limit for imported biocoal is 0 TWh from 2035; only domestic production is allowed	Upper limit for imported biocoal is removed (Sce7)
	Biogas	Upper limit for domestic biogas production is 2.7 TWh	Upper limit for biogas is removed (Sce9)

[1] Comprises the potential for utility-scale ground-mounted PV and building-applied solar PV. Increased technical solar PV potential is allocated to building-applied solar PV technology. This can underestimate the techno-economic potential of solar PV due to the cost differences between utility-scale and building-applied solar PV technologies [96].

[2] In scenario 1 (Sce1), the upper limit is removed for new transmission lines from the offshore wind regions to the neighbouring countries. In scenario 2, the upper limit is removed for new transmission lines from the offshore wind regions to the bidding zones in Norway.

green hydrogen (and ammonia) production in Norway. Consequently, the consumption of hydrogen and ammonia are observed to increase in the industry and transport sectors, respectively in 2035.

6. Discussion

In this study we have examined the major assumptions related to political decisions in energy system optimisation modelling in Norway and how they may influence transition pathway outcomes.

The findings from political feasibility mapping show that the electrification pathway enjoys the most support among Norwegian stakeholder organisations. Electrification of industry and transport is a precondition for shifting consumption from fossil-based energy use to renewable-based electricity. We lack sufficiently detailed data to specify the implications of the actor preferences based on the consultation submissions, but they clearly indicate that electrification – the main strategy of Norwegian energy-carrier decarbonisation – is the most politically feasible. However, we note some challenges for the path ahead.

Combined with the modelling results, our findings help in identifying the technical and politically pertinent implications of electrification. In particular, the land-based wind power installation rates increase manifold when the political assumptions on wind power restrictions are relaxed (as in the "reduced" scenario) – because this is the techno-economically most feasible technology for increasing necessary electricity production. However, it is also the most politically contentious technology. As our modelling indicates that until 2030 there will be few alternatives to land-based wind power, Norway is likely to end up with an electricity deficit. That is not necessarily a problem, depending on the situation in neighbouring countries. However, relying on electricity imports is likely to have implications for electricity prices, at least in some periods.

Notably, the political restrictions in the model play out very clearly in favour of land-based wind power. This is shown in Fig. 4 when restrictions for offshore- and land-based wind power were removed separately. Here, we observe that the removal of the political restriction for land-based wind power can cannibalise model results for offshore wind power restriction. This is due primarily to differences in costs – LCOE differences. We can also observe the effect that expanding variable renewable energy capacity has on the need for further grid development, as presented in Fig. 5. Political decisions about grid development and design such as how and where to connect offshore wind and interconnectors are also politically contentious.

Furthermore, alternatives to land-based wind power are limited, and are mainly to be found within future developments in offshore wind power. This is, however, uncertain and contingent on governmental facilitation and support programmes. There is some potential in solar as well – about 5–10 TWh until 2030, according to a recent Energy Commission report [97] – but this is uncertain and will also require policy support instruments – instruments that as yet have not received favourable signals from the authorities. There are potentials for hydropower and energy savings; these could help – but to a limited degree.

All these factors indicate that key political decision-points for Norway's decarbonisation strategy involve ensuring sufficient electricity production, with two main strategies available: land-based and offshore wind power. We identify the most critical assumptions based on our criteria of being 1) the most technically significant, and 2) the most politically important (involving key political decision points). The political feasibility analysis and the modelling results indicate that the restrictions on land-based and offshore wind power fulfil these criteria.

As land-based wind power remains contentious and of questionable political feasibility, the political choice appears to be between this and the more costly technologies of bottom-fixed and floating offshore wind power. The offshore wind power approach is more politically feasible, but the economic costs may be high, and there is a risk of failure. On the other hand, there is a possible advantage in developing an internationally competitive industry with specific competence within floating wind power.

There are significant elements of path dependency here. As Norway does not have a national gas infrastructure and has invested heavily in electrification, it is unsurprising that there is widespread support for electrification as a decarbonisation strategy. A potential branching point *within* the electrification pathway concerns the choice between on- and offshore wind power – which appears driven primarily by political feasibility. The design of the electricity system, including the interconnectors abroad, will be influenced by choices here, and these decisions will have further implications for the internal grid development, the location of industry [98], and other dimensions of the system. All these should be taken into consideration when making political decisions today.

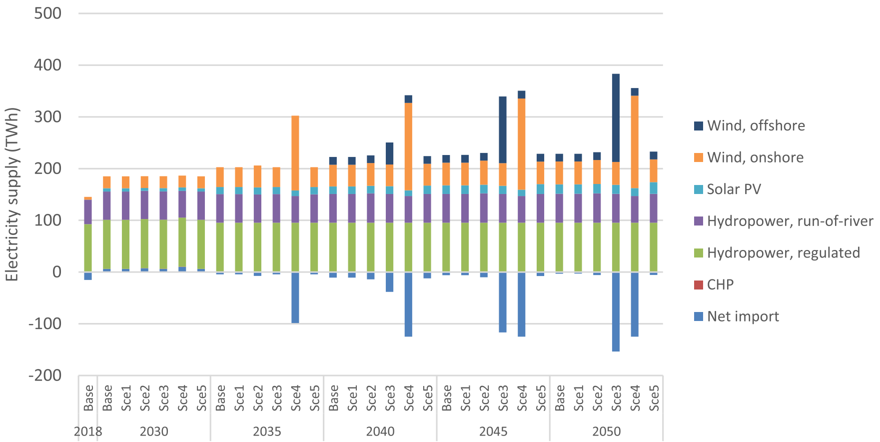

Fig. 4. Electricity supply in Norway until 2050. Negative net import represents net export. Sce1 = transmission lines, international; Sce2 = transmission lines, domestic; Sce3 = offshore wind, Sce4 = onshore wind, Sce5 = solar PV.

Fig. 5. International and domestic electricity trade in Norway until 2050. Sce1 = transmission lines, international; Sce2 = transmission lines, domestic; Sce3 = offshore wind, Sce4 = onshore wind, Sce5 = solar PV.

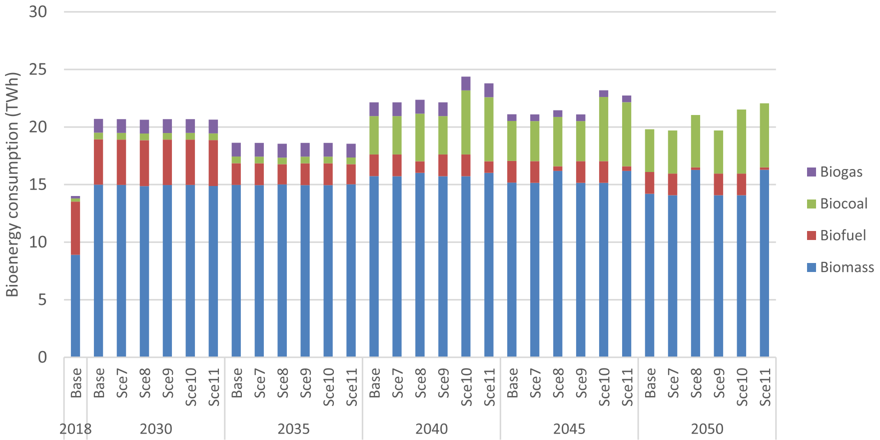

Fig. 6. Bioenergy consumption by fuel type in Norway until 2050. Sce7 = biocoal; Sce8 = biofuel; Sce9; = biogas; Sce10 = biomass; Sce11 = all bioenergy resources (i.e., Sce7–10 combined).

Nor are these choices as clear-cut in practice as they may appear. Policies often end up as compromises and shift over time, and hybrids between the projected results presented here may well emerge. However, the road to decarbonised energy use is not simple. Moreover, electricity supply requires substantial upscaling, and the available paths do not offer simple solutions.

Beyond the electrification pathway, the *bioenergy pathway* has received significant support. As we deem the electrification pathway the most politically feasible, this alternative pathway plays a subordinate, supportive role. This is supported by the modelling, where the biomass

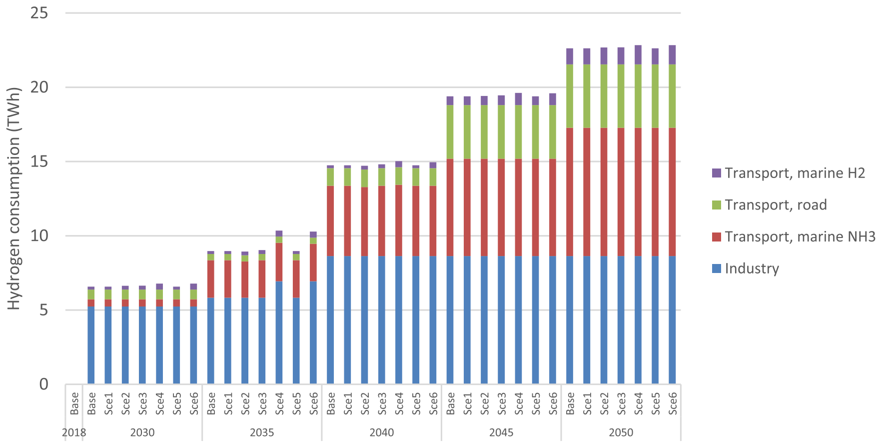

Fig. 7. Hydrogen consumption by sector in Norway until 2050. Sce1 = transmission lines, international; Sce2 = transmission lines, domestic; Sce3 = offshore wind, Sce4 = onshore wind, Sce5 = solar PV, Sc6 = electricity supply and transmission (i.e., Sce1–5 combined).

consumption potential is severely limited by techno-economic criteria in the results. Biogas, for example, has a limited potential even though it is frequently mentioned alongside hydrogen/ammonia in connection with marine transport, industrial processes, and other hard-to-electrify activities. Its limited potential is due primarily to the structure in Norway's land-use sector, where farm effluence and similar represent feedstock for biogas – within a sector where numerous small-scale farms provide this. Most use of biomass concerns the utilisation of forest residues and other similar sources for feedstock.

Hydrogen emerges as the third potential support pathway in combination with electrification. Here, our data may be influenced by stemming from a consultation held in 2020. Although the sector is developing, Norway still has very little commercially operating low-carbon (i.e., green or blue) hydrogen production, as reflected in the *Klimakur* consultation results. Electrolysis-based green hydrogen production may have significant future potential supporting electrification, but this remains uncertain [99]. Regardless, it would entail many of the same political challenges as the electrification pathway, as an electrolysis-based hydrogen production route would require a significant increase in national electricity production. In this study, fossil-based steam methane reformation with carbon capture and storage route (i.e., blue hydrogen) to produce hydrogen was not considered. The blue hydrogen route does not require similar significant additional investments to electricity generation capacity as the green hydrogen route. However, the blue hydrogen route does not provide sector-coupling synergies (e.g., demand response) in a power system where the share of variable renewable resources is expected to increase, such as the green hydrogen route [100]. Previous studies have shown that blue hydrogen can be more competitive route to produce hydrogen in Europe in the mid-term until 2030. However, in the long-term, the competitive aspects were found to disappear [101]. The authors acknowledge that this could have an impact on the hydrogen pathway analysed in this study in the mid-term.

Finally, an energy-saving strategy is not a deep decarbonisation ‘pathway’ as such, as it can only reduce but not replace the use of fossil-based energy carriers in the end-use sectors. Nor does it stand out as a separate cluster, as it has supporters across the various groups. This should be interpreted as a strategy that does not contest any of the other decarbonisation pathways, and should thus be seen as supporting all of the other pathways. This is because all pathways require a significant increase in annual energy produced – which is likely to be a challenge everywhere. In this sense, energy saving should be seen as an enabling factor for all of the pathways.

Thus, the political choices made now are likely to set the direction for the national pathway to net zero. Decisions argued to be ‘technical’ or ‘economic’ may prove to be highly political [29]. However, this analysis has some limitations in treating the actors' interests as largely similar. While this gives a reasonable picture of actor numbers, it may influence the findings as dominant actors are likely to influence policy more than the number of companies suggest. While the cluster weights appear to fit with the dominant interests, as the major sectors (petroleum, renewable electricity) supports the electrification pathway, thereby supporting the main finding, accounting for more structural interest bases and ‘inside’ and ‘outside’ actors may influence the political feasibility attributed to the hydrogen and biofuels pathways. While outside of the scope for this article, this could be accounted for, for example by attributing influence for the companies depending on size and contribution to the national economy.

7. Conclusions

In this study, we have deviated from the standard energy-optimisation modelling practices of aiming to construct the most realistic models, by using modelling to identify the most *politically important* choices in a national energy system. Our aim has been to examine the idea of political feasibility and the role of related assumptions, in energy transition modelling practices, showing how these assumptions may obscure important political decisions for national transition pathways.

We have done this by *identifying the most important assumptions of energy system optimisation modelling, and next, by analysing how these assumptions shape model outcomes and represent crucial political decisions for transition outcomes,* employing a combination of model experimentation, the illumination of model assumptions, and empirically and theory-informed social science analysis of these assumptions.

To achieve this, we first analyse the political feasibility of Norwegian key pathways for decarbonising energy. This is based on interest-based political feasibility theory, with empirical data from a large public consultation disclosing support for different pathways. We here find that the electrification pathway is the most politically feasible transition pathway. Next, we model two main scenarios – one “standard” scenario with all assumed constraints intact, and a “reduced” scenario, where key politically relevant assumptions are relaxed. This is informed by the consultation analysis and enables the identification of the politically most relevant assumptions of the modelling. This moves the ambition of the modelling from increasing the ‘realism’ of the model to discussing the political implications and relevance of the key assumptions.

A key strength of energy system models is that they are logically consistent and are therefore excellent tools for shedding light on key trade-offs in energy systems, and how they can be optimised economically (welfare) and technically. In this study, we have tweaked energy system modelling, by not focusing on the optimal mix of energy supply and demand technologies, but on shedding light on the role of the assumptions themselves, and their role in the political system. It is important to know more about politically acceptable – or *feasible* – solutions and decarbonisation pathways. These pathways entail a wide range of policies and political choices that have received far too little attention in the research literature. Here we have chosen to focus on the case of Norway, which has made progress in the decarbonisation of internal energy carriers.

CRediT authorship contribution statement

Tor Håkon Jackson Inderberg: Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Hilde Andrea Nykamp:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Ville Olkkonen:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Visualization, Writing – original draft, Writing – review & editing. **Eva Rosenberg:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Karianne Krohn Taranger:** Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

Authors report no conflict of interest.

Data availability

The authors do not have permission to share data.

Acknowledgements

We are grateful to the Research Council of Norway for supporting the study under Grant Nos. 295062 and 295704. Thanks also to three anonymous reviewers for constructive input to the manuscript during the review process.

Appendix A. *Klimakur* coding scheme

Category	Description
PW1 Electrification support:	Deep decarbonisation by electrification, electrification as a strategy.
Agriculture	Replacing diesel fuels for agricultural gear and machinery with electricity-driven gear and machinery.
Construction	Replacing diesel fuels for construction gear and machinery with electricity-driven gear and machinery; electrifying the household sector, commercial buildings, and other types of buildings, e.g. by heat pumps.
District heating	Electric boilers and heat pumps.
Heavy industry	Electrification of heavy industry (industry and mining companies).
Household	Electrification through electric heating, e.g. heat pumps.
Offshore petroleum extraction	Electrification through land-fed electricity or offshore windpower.
Service sector	Electrification of the service sector.
Transport	Electrification of cars, coastal ferries, utility vehicles, lorries, long-distance sea transport and aviation.
PW1 Electrification criticism:	Challenges related to the electrification pathway include conflicts over the choice of energy sources to fuel electricity generation; over area and nature encroachment; over strategy, control and participation in the electricity system, over distribution of costs and incomes from electrification, the duration of policy benefits, the environmental and social impacts of el-production, infrastructure, battery production.
Agriculture	Criticism of replacing diesel fuels for agricultural gear and machinery with electricity-driven gear and machinery.
Construction	Criticism of replacing diesel fuels for construction gear and machinery with electricity-driven gear and machinery.
District heating	Challenges related to the electrification of district heating involving the use of electric boilers and heat pumps.
Heavy industry	Challenges related to the electrification of heavy industry and mining companies.
Household	Challenges related to electrifying the household sector through electric heating, for example through heat pumps.
Offshore petroleum extraction	Challenges related to the electrification of offshore petroleum extraction activities, through land-fed electricity or offshore windpower.
Service sector	Challenges related to the electrification of the service sector.
Transport	Challenges related to the electrification of the transport sector.
PW2 Hydrogen support:	Deep decarbonisation through the production and use of hydrogen: green (using renewable energy sources) and blue hydrogen (natural gas with CCS).
Construction	Replacing diesel fuels for construction gear and machinery with hydrogen.
Industry	Use of hydrogen in the industry sector.
Transport	Use of hydrogen in the transport sector, for vehicles and maritime transportation.
PW2 Hydrogen criticism:	Challenges related to the hydrogen pathway.
Construction	Criticism of using hydrogen to replace diesel fuels for construction gear and machinery.
Industry	Criticism of the use and production of hydrogen in the industry sector.
Transport	Criticism of the use of hydrogen in the transport sector, including vehicles and maritime transport.
PW3 Bioenergy support:	Acceleration of sustainable biomass for end-use across sectors. Biomass as energy source for fuels and heat.
Agriculture	Biomass as an energy source, e.g. for machinery or heating of buildings in the agriculture sector.
Construction	Biomass as an energy source in the construction sector, e.g. construction machinery using biogas.
District heating	Use of biomass in district heat production, such as waste, wood chips and bio-oil.
Industry	Biomass as an energy source in industry, such as in forestry-based industries or in other industrial processes.
Transport	Biomass as biofuels for transportation.
PW3 Bioenergy criticism:	Respondents criticise or note challenges related to the bioenergy pathway, including: disagreement over tax exemptions, sustainability issues in forest management, forest as carbon sinks, costs and competition of parallel district heat/electricity networks, climate and sustainability impacts and characteristics of biofuels, national production chains or import from international markets.
Agriculture	Criticism related to biomass as an energy source, e.g. for machinery or heating of buildings in the agriculture sector.
Construction	Criticism related to biomass as an energy source in the construction sector, e.g. construction machinery using biogas.
District heating	Criticism of the use of biomass in district heat production, such as waste, wood chips and biooil.
Industry	Criticism of the production and use of biomass by industry, e.g. in forestry-based industries.
Transport	Criticism of biomass as biofuels in the transport sector.
PW4 Energy saving support:	Improved energy saving and increased energy efficiency across sectors.

(*continued on next page*)

(*continued*)

Category	Description
Buildings and construction	Improved energy efficiency and saving in new and old buildings, e.g. through heating, LED-lights, smart technology and automated energy systems, insulation and other energy-saving/efficient building materials and construction. Greater energy efficiency of machinery on construction and building sites.
Industry	Improved energy efficiency in industry and industrial processes, e.g., heat recovery, reduced heat-loss, new technology.
Transport	Improved energy efficiency of light and heavy transport, sea transport and shipping through technical operational measures.
PW4 Energy saving criticism:	Criticism of/ challenges linked to energy saving and increased energy efficiency across sectors.
Buildings and construction	Criticism of/ challenges linked to energy efficiency and saving in new and old buildings, e.g. heating, LED-lights, smart technology and automated energy systems, insulation and other energy saving/efficient building materials and construction. Greater energy efficiency of machines on construction and building sites.
Industry	Criticism of/ challenges linked to energy efficiency in industry and industrial processes, e.g., heat-recovery, reduced heat-loss, new technology.
Transport	Criticism of/or challenges linked to energy efficiency of light and heavy transport, sea transport and shipping through technical operational measures.

Appendix B. Overview of actors selected for the consultation analysis and in the cluster analysis

No.	Organisation name	Type of organisation
1	Agder Energi AS	Private company
2	Alliansen ny landbrukspolitikk	Interest organisation
3	Animalia, MatPrat, KLF og Nortura	Interest organisation
4	Arbeidsgiverforeningen Spekter	Interest organisation
5	Bane NOR SF	Public company
6	Besteforeldrenes Klimaaksjon	NGO
7	BioFokus	Research organisation
8	Biogass Norge	Interest organisation
9	Biogass Oslofjord	Interest organisation
10	Biokraft AS	Private company
11	Byggenæringens Landsforening	Interest organisation
12	Bømmelfisk AS	Private company
13	CICERO’	Research organisation
14	Circle K, Fortum Charge & Drive, Ionity og BKK	Private company
15	Citizens Climate Lobby Norge	NGO
16	Drivkraft Norge	Interest organisation
17	Dyrevernalliansen	NGO
18	EL og IT Forbundet	Interest organisation
19	Energi Norge	Interest organisation
20	Energigass Norge	Interest organisation
21	Entreprenørforeningen Bygg- og Anlegg	Interest organisation
22	Equinor	Public company
23	Fagforbundet	Interest organisation
24	Fagforeningen Naturviterne	Interest organisation
25	Flowchange	Private company
26	Folkebevegelsen mot klimahysteriet	Interest organisation
27	For Jernbane	Interest organisation
28	Foreningen for Ventilasjon, Kulde og Energi VKE	Interest organisation
29	Fortidsminneforeningen	NGO
30	Fortum	Public company
31	Forum for utvikling og miljø	Interest organisation
32	Framtiden i våre hender	NGO
33	Gasnor AS	Private company
34	Godsalliansen	Interest organisation
35	Grønn Forskning Midt-Norge	Research organisation
36	Grønt Skipsfartsprogram (DNV)	Private company
37	Helse Vest RHF	Public company
38	Helsedirektoratet	Government agency
39	Helsepersonell for plantebasert kosthold HePla	Interest organisation
40	Hovedorganisasjonen Virke	Interest organisation
41	Huseierne	Interest organisation
42	Innovasjon Norge	Public company
43	Jernia AS	Private company
44	KFUK-KFUM Global	Interest organisation
45	Kirkerådet	Interest organisation
46	Klimarealistene	Interest organisation
47	Kolumbus AS	Public company
48	KS Kommunesektorens organisasjon	Interest organisation
49	Kystrederiene	Interest organisation
50	Legenes klimaaksjon	Interest organisation
51	LO Norge	Interest organisation
52	Looping AS	Private company
53	MEF Maskinentreprenørenes forbund	Interest organisation
54	Miljømerking Norge	NGO
55	Monark	NGO
56	N2 Applied	Private company
57	Natur og Ungdom	NGO

(*continued on next page*)

(*continued*)

No.	Organisation name	Type of organisation
58	Naturvernforbundet	NGO
59	NCD alliansen (Kreftforeningen, Diabetesforbundet, LHL, Rådet for Psykisk Helse og Nasjonalforeningen for folkehelsen)	Interest organisation
60	Nelfo	Interest organisation
61	NIBIO	Research organisation
62	NINA Norsk institutt for naturforskning	Research organisation
63	Nissan	Private company
64	NMBU Fakultet for biovitenskap	Research organisation
65	NOAH - for dyrs rettigheter	NGO
66	Norad	Government agency
67	Norges Automobil-Forbund NAF	Interest organisation
68	Norges Bondelag	Interest organisation
69	Norges Fiskarlag	Interest organisation
70	Norges Forskningsråd	Government agency
71	Norges Ingeniør- og Teknologorganisasjon	Interest organisation
72	Norges Lastebileier-forbund	Interest organisation
73	Norges Miljøvernforbund	NGO
74	Norges Røde Kors	NGO
75	Norges Skogeierforbund	Interest organisation
76	Norsk bane (LynTogForum)	Private company
77	Norsk bioenergiforening NOBIO	Interest organisation
78	Norsk Biokullnettverk	Interest organisation
79	Norsk Bonde- og Småbrukarlag	Interest organisation
80	Norsk Eiendom og Grønn Byggallianse	Interest organisation
81	Norsk elbilforening	Interest organisation
82	Norsk Elbåtforening	Interest organisation
83	Norsk Fjernvarme	Interest organisation
84	Norsk Friluftsliv	Interest organisation
85	Norsk Gartnerforbund	Interest organisation
86	Norsk Hydrogenforum	Interest organisation
87	Norsk Industri	Interest organisation
88	Norsk Kommunalteknisk Forening - NKF	Interest organisation
89	Norsk olje og gass	Interest organisation
90	Norsk psykologforening	Interest organisation
91	Norsk Sau og Geit	Interest organisation
92	Norsk senter for økologisk landbruk (NORSØK)	Research organisation
93	Norsk Seterkultur	Interest organisation
94	Norsk Varme	Interest organisation
95	Norsk Varmepumpeforening	Interest organisation
96	Norsk Økosamfunns forening	NGO
97	Norske Boligbyggelags Landsforbund	Interest organisation
98	Norske Havner	Interest organisation
99	NORSKOG	Interest organisation
100	Norsvin SA	Interest organisation
101	Nye Veier AS	Public company
102	Næringslivets Hovedorganisasjon NHO	Interest organisation
103	OmegoFleet	Private company
104	Opplysningsrådet for veitrafikken	Interest organisation
105	Plug Holding AS	Private company
106	Preem Norge AS	Private company
107	Protect Our Winters Norge	NGO
108	Q-separator systems AS	Private company
109	Regnskogfondet	NGO
110	Riksantikvaren	Government agency
111	Rørentreprenørene Norge	Interest organisation
112	Sabima	Interest organisation
113	Samfunnsbedriftene	Interest organisation
114	Sintef	Research organisation
115	Skift Næringslivets klimaledere	Interest organisation
116	Skognæringa Kyst SA	Interest organisation
117	Spire	NGO
118	Spitzberg Holding AS	Private company
119	Statkraft	Public company
120	Statsbygg	Government agency
121	Statskog SF	Public company
122	Stiftelsen Miljøfyrtårn	NGO
123	Syklistenes Landsforening	Interest organisation
124	Tekna	Interest organisation
125	Teknisk beregningsutvalg for klima	Government agency
126	Too Good To Go	Private company
127	Treindustrien	Interest organisation
128	TYR	Interest organisation
129	UN Global Compact Norge	Intergovernmental organisation
130	Uno-X Energi AS	Private company

(*continued on next page*)

(*continued*)

No.	Organisation name	Type of organisation
131	Verdikjeden Skog og Tre	Interest organisation
132	Vestlandsforsking	Research organisation
133	Veterinærinstituttet	Research organisation
134	WWF Verdens naturfond	NGO
135	Zero	NGO
136	Zero Emission Yachting AS	Private company
137	Økologisk Norge	NGO
138	Ålesundregionen Interkommunale Miljøselskap IKS (ÅRIM)	Public company
139	Opplysningskontoret for Meieriprodukter	Private company

Cluster 1

Actor	*Actor type*
Agder Energi AS	Private company
Arbeidsgiverforeningen Spekter	Interest organisation
Bane NOR SF	Public company
Besteforeldrenes Klimaaksjon	NGO
Byggenæringens Landsforening	Interest organisation
Circle K Fortum Charge & Drive Ionity og BKK	Private company
EL og IT Forbundet	Interest organisation
Energi Norge	Interest organisation
Fagforbundet	Interest organisation
Fagforeningen Naturviterne	Interest organisation
Flowchange	Private company
Folkebevegelsen mot klimahysteriet	Interest organisation
For Jernbane	Interest organisation
Fortidsminneforeningen	NGO
Fortum	Public company
Gasnor AS	Private company
Godsalliansen	Interest organisation
Helse Vest RHF	Public company
Hovedorganisasjonen Virke	Interest organisation
Huseierne	Interest organisation
Jernia AS	Private company
KFUK-KFUM Global	Interest organisation
Klimarealistene	Interest organisation
Kystrederiene	Interest organisation
Maskinentreprenørenes forbund	Interest organisation
NAF	Interest organisation
Naturvernforbundet	NGO
NCD alliansen	Interest organisation
Nelfo	Interest organisation
Nissan	Private company
Norges Fiskarlag	Interest organisation
Norges Miljøvernforbund	NGO
Norsk bane (LynTogForum)	Private company
Norske Boligbyggelags Landsforbund	Interest organisation
Norsk Eiendom og Grønn Byggallianse	Interest organisation
Norsk elbilforening	Interest organisation
Norsk Elbåtforening	Interest organisation
Norsk Kommunalteknisk Forening - NKF	Interest organisation
Norsk Seterkultur	Interest organisation
Norsk Varmepumpeforening	Interest organisation
Plug Holding AS	Private company
Protect Our Winters Norge	NGO
Q-separator systems AS	Private company
Riksantikvaren	Government agency
Rørentreprenørene Norge	Interest organisation
Samfunnsbedriftene	Interest organisation
Spitzberg Holding AS	Private company
Statsbygg	Government agency
Statskog SF	Public company
VKE	Interest organisation
Zero Emission Yachting AS	Private company

Cluster 2

Actor	*Actor type*
Equinor	Public company
Norges Forskningsråd	Government agency
Norges Ingeniør- og Teknologorganisasjon	Interest organisation
Norsk Hydrogenforum	Interest organisation
Norsk olje og gass	Interest organisation

(*continued on next page*)

(*continued*)

Cluster 2	
Norsk Økosamfunns forening	NGO
Sintef	Research organisation
Statkraft	Public company
WWF Verdens naturfond	NGO

Cluster 3	
Actor	*Actor type*
Biogass Norge	Interest organisation
Biogass Oslofjord	Interest organisation
Biokraft AS	Private company
Citizens Climate Lobby Norge	NGO
DNV (Grønt Skipsfartsprogram)	Private company
Drivkraft Norge	Interest organisation
Energigass Norge	Interest organisation
Forum for utvikling og miljø	Interest organisation
Framtiden i våre hender	NGO
Grønn Forskning Midt-Norge	Research organisation
Innovasjon Norge	Public company
Kirkerådet	Interest organisation
KS Kommunesektorens organisasjon	Interest organisation
LO Norge	Interest organisation
Miljømerking Norge	NGO
Natur og Ungdom	NGO
NHO	Interest organisation
Norges Bondelag	Interest organisation
Norges Lastebileier-forbund	Interest organisation
Norges Skogeierforbund	Interest organisation
Norsk bioenergiforening NOBIO	Interest organisation
Norsk Biokullnettverk	Interest organisation
Norsk Bonde og Småbrukarlag	Interest organisation
Norsk Fjernvarme	Interest organisation
Norsk Friluftsliv	Interest organisation
Norsk Gartnerforbund	Interest organisation
Norsk Industri	Interest organisation
NORSKOG	Interest organisation
Norsk Varme	Interest organisation
NORSØK	Research organisation
Nye Veier AS	Public company
Opplysningsrådet for veitrafikken	Interest organisation
Preem Norge AS	Private company
Regnskogfondet	NGO
Spire	NGO
Treindustrien	Interest organisation
Uno-X Energi AS	Private company
Verdikjeden Skog og Tre	Interest organisation
Zero	NGO
ÅRIM	Public company

References

[1] A. Grubler, C. Wilson, G. Nemet, Apples, oranges, and consistent comparisons of the temporal dynamics of energy transitions, Energy Res. Soc. Sci. 22 (2016) 18–25.

[2] F.W. Geels, B.K. Sovacool, T. Schwanen, S. Sorrell, Sociotechnical transitions for deep decarbonization, Science 357 (6357) (2017) 1242–1244.

[3] S. Kuhlmann, A. Rip, Next-generation innovation policy and grand challenges, Sci. Public Policy 45 (4) (2018) 448–454.

[4] J. Price, I. Keppo, Modelling to generate alternatives: a technique to explore uncertainty in energy-environment-economy models, Appl. Energy 195 (2017) 356–369.

[5] J.F. DeCarolis, Using modeling to generate alternatives (MGA) to expand our thinking on energy futures, Energy Econ. 33 (2) (2011) 145–152.

[6] S. Pfenninger, A. Hawkes, J. Keirstead, Energy systems modeling for twenty-first century energy challenges, Renew. Sust. Energ. Rev. 33 (2014) 74–86.

[7] A. Gambhir, I. Butnar, P.-H. Li, P. Smith, N. Strachan, A review of criticisms of integrated assessment models and proposed approaches to address these, through the lens of BECCS, Energies 12 (9) (2019) 1747.

[8] A. Nikas, J. Lieu, A. Sorman, A. Gambhir, E. Turhan, B.V. Baptista, H. Doukas, The desirability of transitions in demand: incorporating behavioural and societal transformations into energy modelling, Energy Res. Soc. Sci. 70 (2020) 101780.

[9] J. Jewell, A. Cherp, On the political feasibility of climate change mitigation pathways: is it too late to keep warming below 1.5° C? Wiley Interdiscip. Rev. Clim. Chang. 11 (1) (2020) e621.

[10] E. Trutnevyte, Does cost optimization approximate the real-world energy transition? Energy 106 (2016) 182–193.

[11] W. Peng, G. Iyer, V. Bosetti, V. Chaturvedi, J. Edmonds, A.A. Fawcett, S. Hallegatte, D.G. Victor, D. van Vuuren, J. Weyant, Climate Policy Models Need to Get Real about People—here's how, Nature Publishing Group, 2021.

[12] P.J. Loftus, A.M. Cohen, J.C. Long, J.D. Jenkins, A critical review of global decarbonization scenarios: what do they tell us about feasibility? Wiley Interdiscip. Rev. Clim. Chang. 6 (1) (2015) 93–112.

[13] S.V. Egmond, R. Zeiss, Modeling for policy science-based models as performative boundary objects for Dutch policy making, Sci. Technol. Stud. 23 (1) (2010) 58–78.

[14] G. Savvidis, K. Siala, C. Weissbart, L. Schmidt, F. Borggrefe, S. Kumar, K. Pittel, R. Madlener, K. Hufendiek, The gap between energy policy challenges and model capabilities, Energy Policy 125 (2019) 503–520.

[15] D. Süsser, A. Ceglarz, H. Gaschnig, V. Stavrakas, A. Flamos, G. Giannakidis, J. Lilliestam, Model-based policymaking or policy-based modelling? How energy models and energy policy interact, Energy Res. Soc. Sci. 75 (2021) 101984.

[16] S. Pfenninger, Energy scientists must show their workings, Nature 542 (7642) (2017) 393.

[17] N. Strachan, B. Fais, H. Daly, Reinventing the energy modelling–policy interface, Nat. Energy 1 (3) (2016) 1–3.

[18] A. Silvast, E. Laes, S. Abram, G. Bombaerts, What do energy modellers know? An ethnography of epistemic values and knowledge models, Energy Res. Soc. Sci. 66 (2020) 101495.

[19] M. Fodstad, P. Crespo del Granado, L. Hellemo, B.R. Knudsen, P. Pisciella, A. Silvast, C. Bordin, S. Schmidt, J. Straus, Next frontiers in energy system modelling: a review on challenges and the state of the art, Renew. Sust. Energ. Rev. 160 (2022) 112246.

[20] D. Süsser, H. Gaschnig, A. Ceglarz, V. Stavrakas, A. Flamos, J. Lilliestam, Better suited or just more complex? On the fit between user needs and modeller-driven improvements of energy system models, Energy 239 (2022) 121909.

[21] P. Lopion, P. Markewitz, M. Robinius, D. Stolten, A review of current challenges and trends in energy systems modeling, Renew. Sust. Energ. Rev. 96 (2018) 156–166.

[22] X. Yue, S. Pye, J. DeCarolis, F.G.N. Li, F. Rogan, B.Ó. Gallachóir, A review of approaches to uncertainty assessment in energy system optimization models, Energ. Strat. Rev. 21 (2018) 204–217.

[23] A. Krumm, D. Süsser, P. Blechinger, Modelling social aspects of the energy transition: what is the current representation of social factors in energy models? Energy 239 (2022) 121706.

[24] R.H. Koppelaar, J. Keirstead, N. Shah, J. Woods, A review of policy analysis purpose and capabilities of electricity system models, Renew. Sust. Energ. Rev. 59 (2016) 1531–1544.

[25] Q. Zhu, B.D. Leibowicz, J.W. Busby, S. Shidore, D.E. Adelman, S.M. Olmstead, Enhancing policy realism in energy system optimization models: politically feasible decarbonization pathways for the United States, Energy Policy 161 (2022) 112754.

[26] S. Bolwig, T.F. Bolkesjø, A. Klitkou, P.D. Lund, C. Bergaentzlé, K. Borch, O. J. Olsen, J.G. Kirkerud, Y.-K. Chen, P.A. Gunkel, Climate-friendly but socially rejected energy-transition pathways: the integration of techno-economic and socio-technical approaches in the Nordic-Baltic region, Energy Res. Soc. Sci. 67 (2020) 101559.

[27] R. Hanna, R. Gross, How do energy systems model and scenario studies explicitly represent socio-economic, political and technological disruption and discontinuity? Implications for policy and practitioners, Energy Policy 149 (2021) 111984.

[28] M.A.E. van Sluisveld, A.F. Hof, S. Carrara, F.W. Geels, M. Nilsson, K. Rogge, B. Turnheim, D.P. van Vuuren, Aligning integrated assessment modelling with socio-technical transition insights: an application to low-carbon energy scenario analysis in Europe, Technol. Forecast. Soc. Chang. 151 (2020) 119177.

[29] E. Driver, M. Parsons, K. Fisher, Technically political: the post-politics (?) of the New Zealand emissions trading scheme, Geoforum 97 (2018) 253–267.

[30] D. Rosenbloom, Pathways: an emerging concept for the theory and governance of low-carbon transitions, Glob. Environ. Chang. 43 (2017) 37–50.

[31] F.W. Geels, F. Berkhout, D.P. Van Vuuren, Bridging analytical approaches for low-carbon transitions, Nat. Clim. Chang. 6 (6) (2016) 576–583.

[32] B. Turnheim, F. Berkhout, F. Geels, A. Hof, A. McMeekin, B. Nykvist, D. van Vuuren, Evaluating sustainability transitions pathways: bridging analytical approaches to address governance challenges, Glob. Environ. Chang. 35 (2015) 239–253.

[33] A. Cherp, V. Vinichenko, J. Jewell, E. Brutschin, B. Sovacool, Integrating techno-economic, socio-technical and political perspectives on national energy transitions: a meta-theoretical framework, Energy Res. Soc. Sci. 37 (2018) 175–190.

[34] B.K. Sovacool, J. Axsen, S. Sorrell, Promoting novelty, rigor, and style in energy social science: towards codes of practice for appropriate methods and research design, Energy Res. Soc. Sci. 45 (2018) 12–42.

[35] J. Köhler, F.W. Geels, F. Kern, J. Markard, E. Onsongo, A. Wieczorek, F. Alkemade, F. Avelino, A. Bergek, F. Boons, L. Fünfschilling, D. Hess, G. Holtz, S. Hyysalo, K. Jenkins, P. Kivimaa, M. Martiskainen, A. McMeekin, M. S. Mühlemeier, B. Nykvist, B. Pel, R. Raven, H. Rohracher, B. Sandén, J. Schot, B. Sovacool, B. Turnheim, D. Welch, P. Wells, An agenda for sustainability transitions research: state of the art and future directions, Environ. Innov. Soc. Trans. 31 (2019) 1–32.

[36] F.W. Geels, From sectoral systems of innovation to socio-technical systems: insights about dynamics and change from sociology and institutional theory, Res. Policy 33 (6) (2004) 897–920.

[37] F.W. Geels, J. Schot, Typology of sociotechnical transition pathways, Res. Policy 36 (3) (2007) 399–417.

[38] F.W. Geels, F. Kern, G. Fuchs, N. Hinderer, G. Kungl, J. Mylan, M. Neukirch, S. Wassermann, The enactment of socio-technical transition pathways: a reformulated typology and a comparative multi-level analysis of the German and UK low-carbon electricity transitions (1990–2014), Res. Policy 45 (4) (2016) 896–913.

[39] T.J. Foxon, P.J.G. Pearson, S. Arapostathis, A. Carlsson-Hyslop, J. Thornton, Branching points for transition pathways: assessing responses of actors to challenges on pathways to a low carbon future, Energy Policy 52 (2013) 146–158.

[40] G.C. Unruh, Understanding carbon lock-in, Energy Policy 28 (12) (2000) 817–830.

[41] T.P. Hughes, The Evolution of Large Technological Systems, The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology 82, 1987.

[42] P. Kivimaa, F. Kern, Creative destruction or mere niche support? Innovation policy mixes for sustainability transitions, Res. Policy 45 (1) (2016) 205–217.

[43] C.R. Haddad, V. Nakić, A. Bergek, H. Hellsmark, Transformative innovation policy: a systematic review, Environ. Innov. Soc. Trans. 43 (2022) 14–40.

[44] R.B. Collier, D. Collier, Shaping the Political Arena: Critical Junctures, the Labor Movement, and Regime Dynamics in Latin America, Collier, Ruth Berins, and David Collier, 1991.

[45] K. Lovell, T.J. Foxon, Framing branching points for transition: policy and pathways for UK heat decarbonisation, Environ. Innov. Soc. Trans. 40 (2021) 147–158.

[46] P. Pierson, Increasing returns, path dependence, and the study of politics, Am. Polit. Sci. Rev. 94 (2) (2000) 251–267.

[47] F. Kern, K.S. Rogge, Harnessing theories of the policy process for analysing the politics of sustainability transitions: a critical survey, Environ. Innov. Soc. Trans. 27 (2018) 102–117.

[48] D. Rosenbloom, B. Haley, J. Meadowcroft, Critical choices and the politics of decarbonization pathways: exploring branching points surrounding low-carbon transitions in Canadian electricity systems, Energy Res. Soc. Sci. 37 (2018) 22–36.

[49] IEA, World Energy Outlook, Paris, 2022.

[50] F.G. Li, E. Trutnevyte, N. Strachan, A review of socio-technical energy transition (STET) models, Technol. Forecast. Soc. Chang. 100 (2015) 290–305.

[51] M. Child, C. Kemfert, D. Bogdanov, C. Breyer, Flexible electricity generation, grid exchange and storage for the transition to a 100% renewable energy system in Europe, Renew. Energy 139 (2019) 80–101.

[52] G. Majone, On the notion of political feasibility, Eur J Polit Res 3 (3) (1975) 259–274.

[53] C.J. Stefanou, System development life cycle, in: H. Bidgoli (Ed.), Encyclopedia of Information Systems, Elsevier, New York, 2003, pp. 329–344.

[54] R. Combley, Cambridge Business English Dictionary, Cambridge University Press, 2011.

[55] J. DeCarolis, H. Daly, P. Dodds, I. Keppo, F. Li, W. McDowall, S. Pye, N. Strachan, E. Trutnevyte, W. Usher, M. Winning, S. Yeh, M. Zeyringer, Formalizing best practice for energy system optimization modelling, Appl. Energy 194 (2017) 184–198.

[56] E. Brutschin, S. Pianta, Emissions lock-in, capacity, and public opinion: how insights from political science can inform climate modeling efforts, politics and governance 10 (3) (2022) 186–199.

[57] F. Avelino, J. Grin, B. Pel, S. Jhagroe, The politics of sustainability transitions, J. Environ. Policy Plan. 18 (5) (2016) 557–567.

[58] J. Markard, D. Rosenbloom, Political conflict and climate policy: the European emissions trading system as a Trojan Horse for the low-carbon transition? Clim. Pol. 20 (9) (2020) 1092–1111.

[59] C. Roberts, F.W. Geels, M. Lockwood, P. Newell, H. Schmitz, B. Turnheim, A. Jordan, The politics of accelerating low-carbon transitions: towards a new research agenda, Energy Res. Soc. Sci. 44 (2018) 304–311.

[60] L. Kanger, J. Schot, Deep transitions: theorizing the long-term patterns of socio-technical change, Environ. Innov. Soc. Trans. 32 (2019) 7–21.

[61] B.K. Sovacool, How long will it take? Conceptualizing the temporal dynamics of energy transitions, Energy Res. Soc. Sci. 13 (2016) 202–215.

[62] C. Perez, Technological revolutions and techno-economic paradigms, Camb. J. Econ. 34 (1) (2010) 185–202.

[63] J. Schot, L. Kanger, G. Verbong, The roles of users in shaping transitions to new energy systems, Nat. Energy 1 (5) (2016) 16054.

[64] P. Gilabert, H. Lawford-Smith, Political feasibility: a conceptual exploration, Political Studies 60 (4) (2012) 809–825.

[65] N. Fligstein, D. McAdam, A Theory of Fields, Oxford University Press, 2012.

[66] J. Jewell, A. Cherp, The feasibility of climate action: Bridging the inside and the outside view through feasibility spaces, Wiley Interdiscip. Rev. Clim. Chang. (2023) e838.

[67] V. Lauber, S. Jacobsson, The politics and economics of constructing, contesting and restricting socio-political space for renewables - the German Renewable Energy Act, Environ. Innov. Soc. Trans. 18 (2016) 147–163.

[68] J. Markard, S. Erlinghagen, Technology users and standardization: game changing strategies in the field of smart meter technology, Technol. Forecast. Soc. Chang. 118 (2017) 226–235.

[69] C. Berggren, T. Magnusson, D. Sushandoyo, Transition pathways revisited: established firms as multi-level actors in the heavy vehicle industry, Res. Policy 44 (5) (2015) 1017–1028.

[70] D. Rosenbloom, J. Meadowcroft, The journey towards decarbonization: exploring socio-technical transitions in the electricity sector in the province of Ontario (1885–2013) and potential low-carbon pathways, Energy Policy 65 (2014) 670–679.

[71] P. Johnstone, A. Stirling, B. Sovacool, Policy mixes for incumbency: exploring the destructive recreation of renewable energy, shale gas 'fracking,'and nuclear power in the United Kingdom, Energy Res. Soc. Sci. 33 (2017) 147–162.

[72] M. Howlett, A. McConnell, A. Perl, Weaving the fabric of public policies: comparing and integrating contemporary frameworks for the study of policy processes, Journal of Comparative Policy Analysis: Research and Practice 18 (3) (2016) 273–289.

[73] C. Roberts, F.W. Geels, Conditions for politically accelerated transitions: historical institutionalism, the multi-level perspective, and two historical case studies in transport and agriculture, Technol. Forecast. Soc. Chang. 140 (2019) 221–240.

[74] E. Moe, Energy, industry and politics: energy, vested interests, and long-term economic growth and development, Energy 35 (4) (2010) 1730–1740.

[75] W.A. Maloney, G. Jordan, A.M. McLaughlin, Interest groups and public policy: the insider/outsider model revisited, J. Publ. Policy 14 (1) (1994) 17–38.

[76] K. Araújo, The emerging field of energy transitions: progress, challenges, and opportunities, Energy Res. Soc. Sci. 1 (2014) 112–121.

[77] J. Hogan, The critical juncture concept's evolving capacity to explain policy change, European Policy Analysis 5 (2) (2019) 170–189.

[78] P. Pierson, Politics in Time: Princeton, Princeton University Press, Oxford, 2004.

[79] F.W. Geels, C.C.R. Penna, Societal problems and industry reorientation: elaborating the Dialectic Issue LifeCycle (DILC) model and a case study of car safety in the USA (1900–1995), Res. Policy 44 (1) (2015) 67–82.

[80] P.A. David, Clio and the economics of QWERTY, Am. Econ. Rev. 75 (2) (1985) 332–337.

[81] P. Pierson, Politics in Time History, Institutions, and Social Analysis, Princeton University Press, 2004.

[82] F.R. Baumgartner, B.D. Jones, Agendas and Instability in American Politics, University of Chicago Press, 2010.

[83] L.F. Hirt, G. Schell, M. Sahakian, E. Trutnevyte, A review of linking models and socio-technical transitions theories for energy and climate solutions, Environ. Innov. Soc. Trans. 35 (2020) 162–179.

[84] Kristina Haaskjold, Eva Rosenberg, Pernille Merethe Sire Seljom, Lisa Kvalbein, Documentation of IFE-TIMES-Norway v3, 2022.

[85] R. Loulou, A. Lehtilä, A. Kanudia, U. Remme, G. Goldstein, Documentation for the TIMES Model: Part II Reference Manual, 2016.

[86] S. Backe, C. Skar, P.C. del Granado, O. Turgut, A. Tomasgard, EMPIRE: an open-source model based on multi-horizon programming for energy transition analyses, Softwarex 17 (2022).

[87] Ministry of Transport, National Transport Plan 2022–2033 *(In Norwegian: Nasjonal transportplan 2022-2033)*, 2021.

[88] T.N.W.R.a.E.D. (NVE), Langsiktig kraftmarkedanalyse 2020–2040 (Long-term Power Market Analysis 2020–2040), 2020.

[89] S.N. (SSB), Electricity. https://www.ssb.no/en/statbank/table/08307, 2022 (Accessed 28.3.2023).

[90] T.N.W.R.a.E.D. (NVE), Ny kraftpduksjon 1. kvartal 2020 (New Power Generation). https://www.nve.no/energi/analyser-og-statistikk/ny-kraftproduksjon/, 2020.

[91] NVE, Vindkraftdata. https://www.nve.no/energiforsyning/kraftproduksjon/vindkraft/vindkraftdata/, 2020.

[92] K.S. Berg, M. Carlsen, T. Eirum, S.B. Jakobsen, N.H. Johnson, S.K. Mindeberg, K. Nybakke, G. Sydnes, Havvind-Strategisk konsekvensutredning, NVE-Norges vassdrags-og energidirektorat, 2012.

[93] D. Bogdanov, J. Farfan, K. Sadovskaia, A. Aghahosseini, M. Child, A. Gulagi, A. S. Oyewo, L. de Souza Noel Simas Barbosa, C. Breyer, Radical transformation pathway towards sustainable electricity via evolutionary steps, Nat. Commun. 10 (1) (2019) 1077.

[94] E.E.A. (EEA), EEA Technical report No 6/2009 Europe's Onshore and Offshore Wind Energy Potential - An Assesment of Environmental and Economic Constraints, EEA Technical Report, 2009.

[95] M.o.P.a. Energy, Act No. 82 of 24 November 2000 relating to river systems and groundwater (Water Resources Act), 2000.

[96] Danish energy agency, Technology Data - Generation of Electricity and District heating, 2022.

[97] Energikommisjonen, Mer av alt - raskere in: M.o.P.a. Energy (Ed.) NOU Norges offentlige utredninger OSLO, 2023.

[98] M.L. Larsen, K. Dupuy, Greening industry: opportunities and challenges in electricity access for Norwegian industry firms, J. Clean. Prod. 136534 (2023).

[99] S. Alvik, M. Rinaldo, O. Özgün, F. Berglund, T. Horschig, A.L. Koefoed, S. Selvakkumaran, A. Zambon, Energy Transition Norway 2022: A National Forecast to 2050, 2023.

[100] H. Lange, A. Klose, W. Lippmann, L. Urbas, Technical evaluation of the flexibility of water electrolysis systems to increase energy flexibility: a review, Int. J. Hydrog. Energy 48 (2023) 15771–15783.

[101] G. Durakovic, P.C.D. Granado, A. Tomasgard, Are green and blue hydrogen competitive or complementary? Insights from a decarbonized European power system analysis, Energy 282 (2023).