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Exploring the Factors Leading to Diffusion of Alternative Fuels Using a Socio-Technical Transition Approach—A Case Study of LNG as a Marine Fuel in Norway

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Abstract: The maritime shipping sector needs to transition towards a low- or zero-emission future to align with the 1.5 °C temperature goal and the recently adopted and revised greenhouse gas (GHG) strategy at the International Maritime Organization (IMO). A significant research gap exists in understanding how socio-economic and socio-political processes can lead to the adoption of alternative marine fuels that will be essential in meeting the aforementioned goals. The aim of this paper is to use a case study of an existing transition to understand how diffusion takes place, specifically how the adoption of liquified natural gas (LNG) in Norway has unfolded and what lessons can be learnt from this process. To answer this question, a combination of semi-structured interviews with key maritime stakeholders and documentary evidence was collected covering the period from 1985 to 2015. The collected data were analysed through a content analysis approach applying the multilevel perspective (MLP) as a heuristic. The qualitative results paint an interesting picture of the changing attitudes towards LNG as a marine fuel in Norway. In the early years, the adoption of LNG was primarily driven by air pollution and political considerations of using Norwegian natural gas, which over time, evolved into a more focused maritime paradigm painted through the lens of the Norwegian maritime industry under wider regulatory developments such as emission control areas (ECAs). By the 2010s, these drivers were superseded by GHG considerations such as methane slip concerns and a less favourable natural gas market leading to a slowdown of LNG adoption. These findings provide valuable insights for understanding future adoption dynamics of alternative zero-emission fuels, particularly in relation to the role of strong technology champions, institutional modification requirements, and starting conditions for a transition.

Keywords: liquified natural gas as a marine fuel; sustainability transitions; multilevel perspective; Norway

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1. Introduction

The maritime shipping industry is responsible for over 2.89% of global anthropogenic greenhouse gas (GHG) emissions [1]. Shipping is also a significant contributor to air pollution, in particular sulphur oxide (SOx), nitrogen oxide (NOx), and particulate matter (PM) emissions [1]. The United Nations Sustainable Development Goals (UNSDGs) highlight the importance of lowering air pollution to reduce deaths and illnesses from air pollution (UNSDG target 3.9.1) and outline the need for urgent action to combat climate change (UNSDG goal 13) [2]. In 2023, the International Maritime Organization (IMO) agreed on the '2023 IMO GHG Strategy', with ambitions to decarbonise the shipping industry by or around 2050 [3]. To accomplish this goal, the maritime industry will need to adopt new marine fuels, with zero or near-zero lifecycle GHG emissions [4]. It remains to be seen how the adoption dynamics for these new fuels will unfold. Liquefied natural gas (LNG) due to its GHG emissions has significant challenges in providing a viable decarbonisation path for shipping [5] but has been an important maritime alternative fuel in the past [6,7] and as such can provide valuable insights into how a transition to a new fuel in the shipping industry can unfold [8].

The major alternative fuels for maritime transport (i.e., LNG, biofuels, methanol, hydrogen, and ammonia), have all, to varying degrees, been seen as part of the solution to lowering both air pollutants and GHG emissions [9]. Air pollutants and greenhouse gas (GHG) emissions from ships are known for their long-term environmental effects [10]. The rapid spread of LNG as a ship fuel in Norway during the decade of the 2000s was heralded as a potential path to a more sustainable maritime transport industry [11]. In addition, the early geographic concentration of LNG-fuelled vessels in Norwegian coastal waters has been attributed to favourable local and regional conditions [12,13], supported by wider socio-economic trends [14].

For many years, air pollutant impacts of various marine fuels have been well studied [15]. Many have highlighted the net benefits of LNG compared to heavy fuel oil (HFO) and distillate fuels when it comes to significantly lower sulphur oxide (SOx), nitrogen oxide (NOx), and particulate matter (PM) emissions [16]. SOx and NOx have been identified as significant contributors to acidification and eutrophication, leading to negative effects on the natural environment [17,18]. These same air pollutants have also been linked to adverse health effects [19], especially regarding the respiratory system [20], and risk creating possible negative economic effects [21]. Such emission reductions, especially in terms of NOx reductions, were quite apparent when the 1988 Sofia Protocol [22] and the 1999 Gothenburg Protocol [23] entered into force. It should be noted that the same benefits LNG shares with other fuels, such as hydrogen, ammonia, and methanol, have the added benefit of being produced from non-fossil sources and can bring about significantly lower GHG emissions compared to LNG [24].

In the case of LNG, GHG abatement benefits are limited [16,25]. Studies have offered a range of figures, depending on how methane leakage and upstream emissions are accounted for, and as a result, LNG is not a viable long-term option for use as an alternative fuel to decarbonise maritime shipping [7,16,25]. LNG developments outside of Norway, as well as GHG and air pollutant emissions of LNG as a marine fuel are beyond the scope of this study and are only touched upon in terms of where they are of consequence to socio-political and socio-economic developments. The focus of this study is a socio-technical historical analysis of the adoption of LNG as a marine fuel followed through the lens of actors, regulations, and narratives which supported its adoption. The aim of this study is not to present LNG in either a positive or negative light or to provide a value judgement on historical benefits of its adoption, but to use the case study period (i.e., 1985–2015) which covers the most intense period of LNG adoption in Norway to understand the adoption dynamics of LNG as a marine fuel from a socio-technical perspective. The hope is that understanding this process can provide lessons for adoption of alternative fuels such as methanol, hydrogen, and ammonia.

Previous socio-technical studies analysing the adoption of LNG as a marine fuel tended to overlook early developments taking place in the 1980s and 1990s [6,26,27]. Additionally, many studies only focused on documentary evidence for the analysis [6,26] which do not utilise the rich qualitative information interviews can provide [28]. Where interviews were applied, this was performed to cover a much shorter period and included significantly fewer interviews [27]. This study aims to address these gaps by going much further into the past to adequately understand the socio-political and socio-technical backgrounds underpinning the adoption dynamics of LNG. In this process, rich insights from key stakeholder interviews can paint a clear understanding of the dynamics of the process [28]. It could be argued that the current transition to zero or near-zero marine fuels is also at a similar early adoption stage as LNG was in the 1990s, and understanding the progression from this early 'emergence' phase of the transition to the 'diffusion' phase [29] could offer some valuable insights for future fuel transitions.

Furthermore, even when considering the limitations of LNG as a ship fuel, the understanding of this fuel transition, in connection with how the maritime industry in general has changed over this period, can provide valuable insights into the nature of fuel transitions in shipping. There is currently limited understanding of what role wider socio-technical parameters, protective spaces, and local geographic conditions can have on directing maritime sustainability transitions. To accomplish this, the paper asks the following research question:

- How did the adoption of LNG in Norway unfold and what lessons can be learnt from this process?

Through answering this research question, this paper provides novel empirical contributions to the historical understanding of socio-political and socio-technical adoption dynamics of LNG as a marine fuel, especially in the early formative years of the 1980s and 1990s. Secondly, this paper provides a unique empirical case study from which inferences can be drawn in reference to the adoption of other alternative marine fuels such as hydrogen and ammonia. In addition, this paper provides a much deeper empirical understanding of the socio-political dynamics of LNG fuel adoption than was provided in other empirical work. From a conceptual perspective, this paper provides a novel application of the socio-technical transition framework where a deeper understanding of the interactions between socio-technical regime actors in a political space takes place. Additionally, the rich number of primary sources of evidence gathered through interviews and documentary evidence provides a good example of an in-depth application of the multilevel perspective (MLP) heuristic to a maritime case.

2. Literature Review

Limited research has been undertaken to understand the history of how, when, and why LNG started to be used as a marine fuel. The socio-technical transition lens has been applied previously in several marine case studies in the case of LNG [6,26,27] energy transitions in the context of maritime decarbonisation [30] and transition from wind to steamships [31]. However, a deeper understanding of how the socio-technical lens interacted with the wider political developments, especially in the 1990s and 2000s, remains largely understudied, with limited expansion of how growing environmental and energy security pressures affected these developments.

The literature review of relevant articles was carried out through a keyword search and citation analysis to identify the most relevant articles pertaining to 'LNG as a ship fuel' developments in northern Europe (Figure 1). The undertaken citation analysis showed that most of the relevant articles were published after 2009, with a general peak in articles occurring during 2014–2022.

A large proportion of articles seem to deal with the technical, environmental, and safety aspects of LNG as a marine fuel. The great majority of technical and environmental articles deal with the modelling and estimation of air emissions from LNG-fuelled vessels (primarily SOx, NOx, PM, and GHGs). A significant number of articles cover various aspect of LNG markets, which include some analysis of either socio-technical or socio-political components driving their developments but only look at wider LNG market developments and briefly mention 'LNG as a marine fuel'-related developments [32–34]. In addition, articles that deal with LNG as a marine fuel tend to include LNG as one of many options, such as distillates or renewables, and provide limited qualitative insights. Most such articles provide quantitative forecasts of LNG infrastructure/operating costs [35–39], future demand for LNG [40,41], and quantitative emission or investment comparisons of LNG to other fuels [42,43] with limited insights about the historical development of LNG as a ship fuel. Most socio-economic insights tend to only be used to describe different future fuel demands, infrastructure developments, or market barrier models [36,44,45].

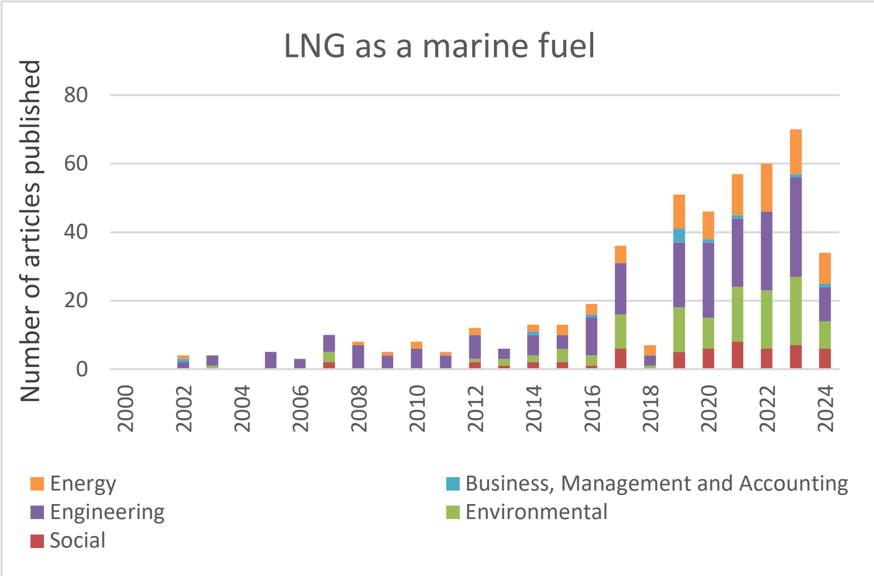


Figure 1. Academic articles covering 'LNG as a marine fuel' developments by year (The analysis used the SCOPUS scientific database [46]. The research analysis began with a keyword search for a various relevant keyword (i.e., 'LNG', 'marine LNG', and 'LNG as a ship fuel') covering the period from January 1990 to April 2024. The 'Abstracts' in the large number of articles obtained (over 500) were skim-read to identify articles with relevance to LNG developments as a ship fuel).

Furthermore, only a few articles provide a more longitudinal description of historical LNG developments [47–50], touching upon some non-market factors and their role in shaping the maritime LNG industry. Most such articles are non-maritime LNG-specific but deal with the wider LNG industry [33,48,50]. The ones that are maritime LNG-specific [51,52] deal with non-market forces in a limited manner. Work by some [50] provides more insights into such developments, but is global in nature, without deeper insights into specific unique circumstances taking place in northern Europe. Other work [41,53,54] tends to be limited in analytical scope [53] or looks at a singular highly localised case study [41,54]. This paper tries addressing the research gap surrounding the socio-technical adoption dynamics of LNG as a marine fuel in Norway.

3. Materials and Methods

The conceptual framework of this paper is embedded in literature on 'sustainability transitions', dealing with 'socio-technical systems' and their 'reorientations' to increasingly sustainable arrangements [55,56]. The underlying 'heuristic' used as a conceptual framework for this article is the MLP [31,57]. The MLP heuristic emphasises the role that 'protective spaces' can have in guiding and nurturing the development of a new technology and presents sustainability transitions as multidimensional processes [58,59], where industry and policy actors within their embedded regimes can affect and be affected by 'protective space' developments and outside forces [60].

The MLP recognises that socio-technical transitions occur through interactions between three levels, these being the niche, regime, and landscape. The regime is the embedded industry configuration, which includes current technologies, institutional configurations, and practices; niches are 'protective spaces' where new innovations can take hold and are generally shielded from regime-level pressures, whilst the landscape is the set of outside 'exogenous' forces which can destabilise the regime, such as market pressures, wars, and environmental changes.

As outlined in Figure 2, once the MLP was applied, a data collection procedure was outlined using MLP conceptual categories for collecting qualitative data and preparing interview questions. Once the data collection procedures were outlined, the data collection was undertaken. Primary documentary data sources included monthly editions of

Maritime Reporter monthly magazine from 1985 to 2015, which were taken as proxies for developments in the maritime transportation industry and *Lloyd's List* database [61] from 1985 to 2015; both were taken as proxies for what was reported to be happening regarding LNG in Norway. In addition, Norwegian Shipowners' Association annual reports for the study period were also analysed, using a relevant keyword search. The collected data were explored in more detail through in-depth search and analysis of relevant archival information covering development of laws and regulations for LNG and maritime transport in the Norwegian Parliament.

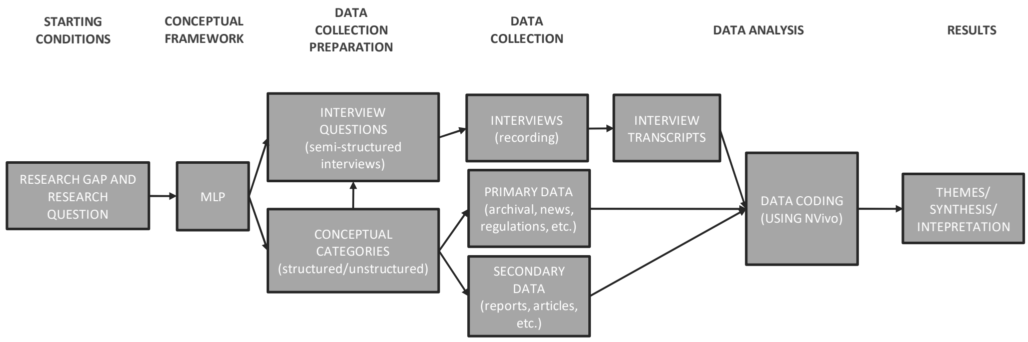


Figure 2. Flowchart illustrating data collection and analysis process.

These data were triangulated with 41 semi-structured interviews with key actors who had first-hand knowledge of Norwegian marine LNG developments (Appendix A). The interviews provided a range of deep-level insights, and care was taken that the interviewees covered diverse backgrounds. The interviewees had a high degree of understanding of the subject matter with 51% being senior corporate executives driving LNG developments and over 70% having over 10 years of relevant LNG experience (Appendix D). In line with Creswell [28], preliminary research was used to initiate a snowball sampling method [62,63]. This approach aligned with a principal aim of process tracing which is to identify key actors that had most involvement in 'processes of interest' [63]. To ensure a representative sample of relevant interviewees was obtained, the interviewees were asked about other potential people to interview, and this process was repeated through multiple interview stages and was stopped once names of interviewees started reappearing, assuming 'saturation' took hold [64,65]. To avoid selection bias, a balance was sought by including actors from multiple levels of society and representing 'opposing positions' [66]. In this way, statements made by interviewees could be compared and verified, whilst also being triangulated with documentary evidence. The sampling method achieved a 41% response rate (Appendix C), with the obtained sample size believed to be sufficient to achieve the goals of this paper [67,68]. Steps were also taken to avoid personal bias, through self-reflection [28].

The interviews were undertaken over a 6-month period. They lasted an average of between 60 and 90 min and were all recorded, transcribed, and thematically analysed. The interviews were conducted in a semi-structured manner, with open-ended questions intended to obtain as much information as possible, giving the interviewees a chance to state their own opinion and open the conversation. Unlike surveys, the aim of these in-depth interviews was not only to collect similar information from all interviewees but also to tap into their unique knowledge of the processes they experienced. Such 'in-depth' interviews [68] were used as a key source of rich qualitative historical information. Key issues were explored through follow-up questions [69]. For each interview, an 'interview protocol' was prepared (Appendix B). Care was taken to avoid 'leading' questions that could 'put words' in interviewees mouths [70]. Interviewees were explained the interview process in advance. The interviewees were guaranteed anonymity to allow for openness.

The collected information was analysed using qualitative content analysis [71], with coding categories that included analysis of 'meanings of words' whilst applying a content analysis approach [72]. The coding process was performed using NVivo (Version 11) qualitative analysis software in order to better manage the analysis process [73].

The primary data were further triangulated with the secondary literature to increase the internal validity and repeatability of the research [74]. Data analysis was undertaken using a process tracing approach [75], and the results are presented through a historical narrative [76]. The results were arranged into conceptual categories relevant to the findings.

4. Results

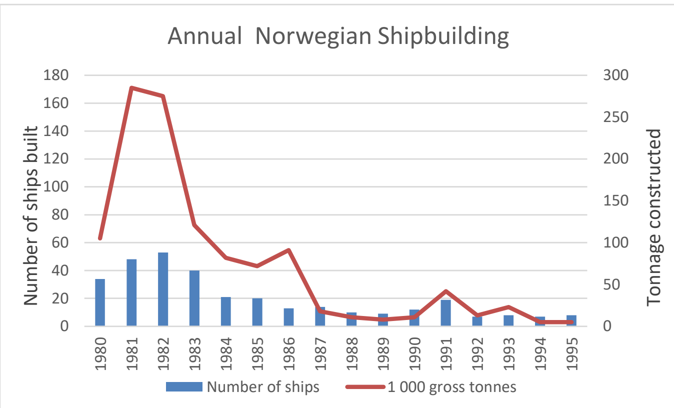
Using the MLP and the socio-technical lens, this section presents a thorough historical narrative of LNG developments in Norway from 1985 to 2015, broken down into eight time periods. The content analysis and interviews are used to provide a chronological narrative of maritime LNG developments over time and space to paint a rich picture of the diffusion.

4.1. 1981–1996 Co-Evolution of Politics, Natural Gas Industry, Domestic Gas Engines, and Shipbuilding in Norway

The period from 1981 to 1996 saw profound 'landscape' pressures destabilising the Norwegian socio-technical regime. These changes affected the national political scene, shipbuilding industry, and natural gas (NG) engine technological developments. The combination of a reorientation within the Norwegian shipbuilding industry towards more specialised developments of ferries and platform supply vessels (PSVs) catering to the oil and gas industry occurred simultaneously with growing oil and gas exploration activities. This in turn happened during a time of increased 'niche' innovation by the Norwegian engine manufacturer 'Bergen Ulstein AS', with respect to spark- ignition gas engines.

On a landscape level, the OPEC (Organization of the Petroleum Exporting Countries) oil crisis of the 1970s led to a marked decrease in demand for oil tankers and was a significant blow to shipbuilding industries of many Scandinavian countries, including Norway [77]. This global crisis continued into the 1980s and had a profound effect on European shipbuilding, coupled with stronger international competition from East Asian shipyards.

The 1970s and 1980s saw a significant increase in East Asian shipbuilding, whilst western European shipbuilding went through a process of downscaling [78]. The late 1970s saw a drastic decrease in new tanker orders from Norwegian shipyards [79], and during the 1980s, the Norwegian shipbuilding output fell by almost 90% (Figure 3). In response, Norwegian shipyards reoriented from the construction of large bulk carriers and crude oil tankers to a specialised 'offshore focus' [78]. This reorientation was in line with a large increase in Norwegian oil and gas exploration.



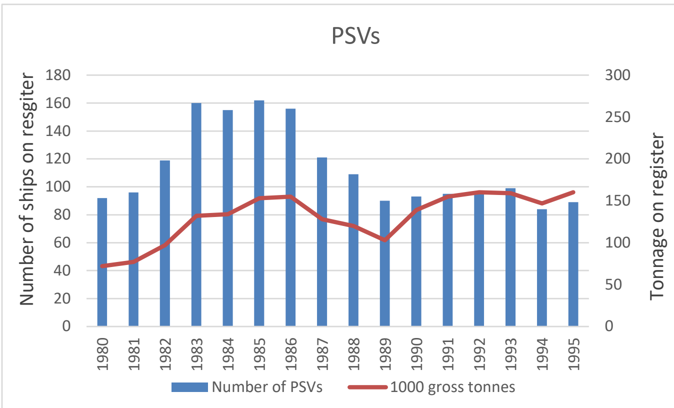


Figure 3. Norwegian shipbuilding vs. platform supply vessel (PSV) developments, 1980–1995 (Data collected from multiple archival reports, available from Statistics Norway [80]).

In addition, during the 1980s, the role that natural gas played in society also started to change. The 1980s in Norway began with a political shift to the right, resulting in the election of the Conservative Prime Minister, Kare Willoch [81].

These societal changes, in combination with new natural gas field discoveries, had profound effects on the Norwegian 'regime'. During the 1980s, the Norwegian state-controlled national oil company Statoil took over operations of several high-profile fields. In 1984, the large Snohvit gas field was discovered [82]. Due to its distant position within the northern end of the Norwegian continental shelf, transport via gas pipelines seemed quite expensive, providing an incentive for the development of LNG ship exports [82]. At the same time, from 1st January 1985 the new conservative government decided to establish the 'State's Direct Financial Interest' (SDFI) [83]. The SDFI split Statoil's license interests into a financial component for the Norwegian State and a separate company component, increasing government control over Statoil's business [82]. Hunter [84] has argued that the purpose of this move was in response to the growing political and economic power of Statoil in the 1980s, and the conservative government moved to curtail this power. The trend towards further gas discoveries and Statoil's involvement in oil and gas operations continued during the 1980s, with Statoil taking over operations of the high profile 'Stratfjord' oil field in 1986 [81]. In the same year, Statoil started production at the Gullfaks oil field [81]. Such high-profile developments led to the economic 'solidification' of Norwegian state control over oil and gas production [81].

During the 1980s, first piped natural gas landed at Karsto in Rogaland [85]. However, the Norwegian gas network remained underdeveloped, possibly due to low population densities [85]. In addition, ever since the 1950s, Norway has produced most of its electricity from hydropower [86]. This geographic situation and low domestic natural gas demand was curtailing the development of a domestic natural gas market and played a key role in the way that Norwegian policymakers would manage Norway's natural gas resources. In this 'regime' environment of increasing state control over oil and gas production, the Norwegian state approved the development of the large 'Sleipner East' and 'Troll' gas fields in 1986 [87]. The late 1980s in Europe saw a general trend towards higher natural gas use that in the UK was reinforced by the liberalisation of the electricity market, providing additional demand for Norwegian gas [88].

In 1987, in this climate of growing awareness of the importance of natural gas for the future of Norway, the 'Research Council of Norway', a government agency, initiated the SPUNG programme ('Statlig programme for utnytting av naturgass'/'State programme for utilisation of natural gas'). The programme ran from 1987 to 1994, with mixed public–private funding [89,90] specifically aimed at developing technologies and research competencies for natural gas in Norway [90,91]. It was initiated at a time of falling oil prices and growing oil production (Figure 4). In 1994, SPUNG was superseded by a new Research Council-funded programme, GAVOT ('Gas Research-Products and Services'/'Gassforskning—varer og tjenester') which offered increased opportunities for private funding, lasting from 1994 to 1998 [85]. The specific aim of the programme was to "...increase value creation in Norway based on our gas resources by laying the technological foundation for the development of gas-related equipment and services, or by increasing the value of Norwegian gas exports" [85].

In this period of changing regime orientations, 'niche' actors first started experimenting with LNG as a marine fuel. The first academic inquiry in Norway for the potential use of natural gas as a ship fuel was carried out in 1989, but not much action was taken due to the perceived high costs [92]. This coincided with the first global application of natural gas as a marine fuel that took place in Canada [92,93].

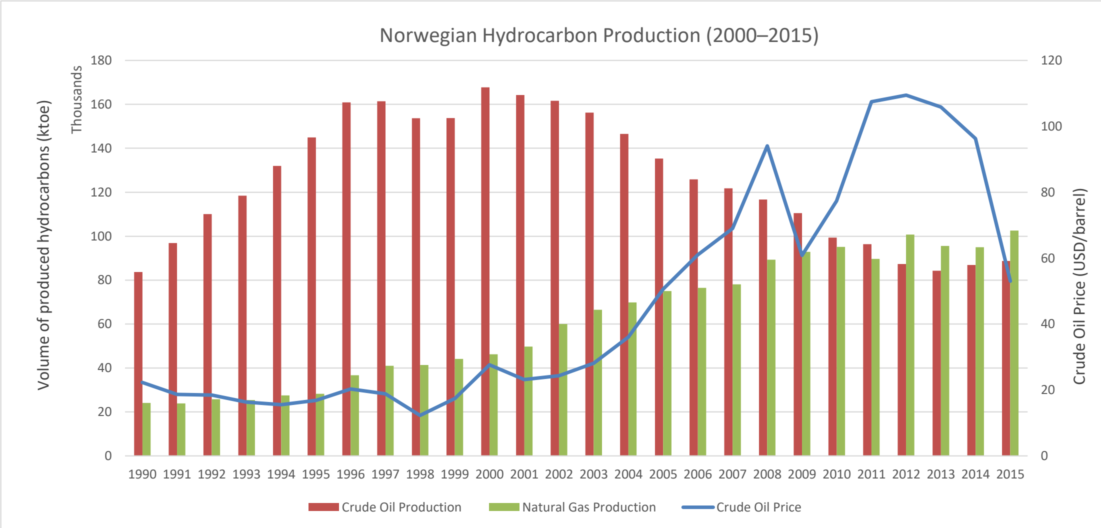


Figure 4. Norwegian production of natural gas and crude oil vs. Brent crude oil prices (Brent prices are given in money of the day, based on IEA [94]).

4.2. 1987–2000 Norway on the Path towards the First LNG-Fuelled Vessel

In the late 1980s, the wider Norwegian political landscape was changing under growing attention to environmental issues. In 1987, the 'Brundtland Report' was published and set the stage for a global discussion around sustainable development [95]. The report drew on conclusions from the 1972 'Stockholm Conference' and aimed at developing a global legal framework for environmental conservation. The chair of the World Commission on Environment and Development (WCED), under whom the report was published, was Gro Harlem Brundtland, Prime Minister of Norway from 1990 to 1996 [96]. During the period of Ms Brundtland's government, there was a strong commitment for a wide and 'overarching' environmental strategy [97]. It should be noted that the success of some of these initiatives and their long-term effects were later brought into question [98].

During the 1989 election, environmental issues were the second most important electoral issue for voters [99]. The generally positive political atmosphere towards environmentalism was occurring, while Norway was also pushing the SOx emission agenda at the IMO. Politically speaking, the 1990s would start with increasing international discussions relating to global anthropogenic climate change emissions. In 1988, the Intergovernmental Panel on Climate Change (IPCC) was established and by November 1990, IPCC and the Second World Climate Conference started calling for a global treaty on GHG emissions, resulting in the United Nations Framework Convention on Climate Change (UNFCCC) in 1994 and the adoption of the Kyoto Protocol in 1997 [100]. During the late 1980s and early 1990s, NOx emission concerns were also becoming more prominent in Scandinavia and Norway.

In Norway, the late 1980s also saw increasing political instability that was partly a result of the oil price crash of the late 1980s and of increasing unemployment linked to shipyard closures and loosing oil revenue [101]. During the early 1990s, the oil price started recovering and the Norwegian Government created a 'Government Petroleum Fund' [102], with the aim of preserving oil and gas revenues for future generations [103]. This was happening at a time when the global natural gas market was maturing and becoming a seriously traded global commodity, whilst sales of Norwegian natural gas continued to grow (Figure 5). In 1990, for the first time, a futures contract for natural gas was created by the New York Mercantile Exchange (NYMEX) [104].

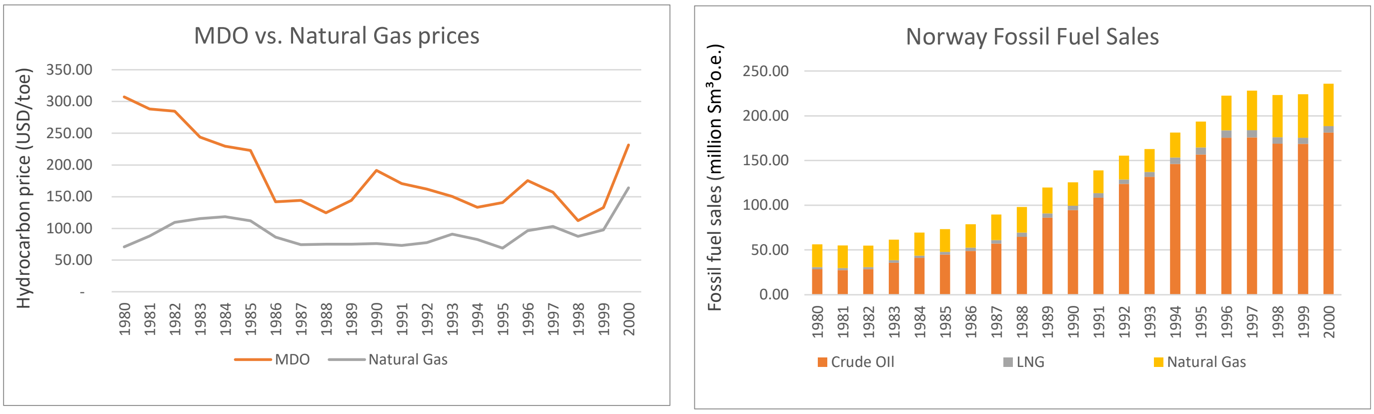


Figure 5. Fossil fuel prices and Norwegian fossil product sales, 1980–2000 (Data presentation made by authors based on own analysis and information from Clarkson's [105] and Norwegian Petroleum Directorate [106]. Prices are given in money of the day.)

The coming together of two political desires, namely the domestic utilisation of natural gas and reduced NOx emissions, spearheaded the development of natural gas-fuelled ferries in the early 1990s. Interviewee 30 states that "…if we look a little bit historical, we have had a very, very important Prime Minister in Norway, Gro Harlem Brundtland, and she brought, brought the, the, emission, the climate, the climate question environmental question on the political table on the beginning of the 90s in a very strong way".

The stage was now set for a more concerted 'regime' push for the domestic utilisation of natural gas. In June 1990, Norway passed the 'Energy Act' [102], liberalizing Norwegian power markets [102]. In December of the same year, the 'Regulations concerning the generation, conversion, transmission, trading, distribution and use of energy' [107] were also passed. The regulations specifically stipulate that all energy plans that deal with the generation, transmission, distribution, and use of electrical energy will give consideration to "possibilities for the use of district heating… domestic consumption of gas…".

In 1991, in the context of rising domestic concerns around climate change, Norway passed a carbon tax and banned permanent gas flaring from oil and gas fields [108]. However, the maritime transport industry was exempt from this tax [109].

This same period saw a significant increase in the taxes imposed on sulphur content in fuels [110]. In 1990, the Norwegian Ministry of Environment, the Pollution Control Authority (SFT), and Norwegian Maritime Directorate started drafting regulations concerning NOx emissions from ships [111]. However, these regulations were 'put on ice' and a decision was made in 1990s, to prepare an 'action plan' for NOx and carbon dioxide (CO_2) emissions [111]. In light of these developments, in 1991, the Norwegian Government (analysis of Norwegian Government document archive [112], during 1985–2015, for keywords naturgass, Naturgass pa ferje, MRF, Fjord1, Glutra, and LNG based on the process of elimination, and the overall number of hits was lowered to a manageable number, and these were opened and researched further using keywords to identify key paragraphs which were translated into English) gave an assignment to MARINTEK to cooperate with the Norwegian Maritime Directorate on the Royal Norwegian Council for Scientific and Industrial Research (NTNF) project, 'Environmentally friendly ships'. Under the project, one of the support solutions for NOx emissions was, "…fuel technology measures". However, at this time, the Norwegian Government's 'Norwegian Official Report (NOU) document makes no mention of gas [111].

This project is an early example of 'niche–regime' interactions concerning LNG as a marine fuel in Norway. By this point, MARINTEK was a key Norwegian marine LNG niche player. Since the early 1980s, MARINTEK had already been collaborating on natural gas developments with other 'niche' actors, such as Bergen Ulstein on natural gas engines [85] and was already as of 1989 researching marine applications of natural gas [92].

By 1993, political support for natural gas ferries had grown considerably. This was happening at a time of some renewed optimism surrounding the shipbuilding industry (Figure 6). In 1993, the Norwegian Ministry of Transport and Communication approved the decision to start research into the potential use of natural gas as a ship fuel for ferries [85]. This decision was intended to provide funding for research into a possible conversion to gas of a single engine on the MF 'Rennesoy' ferry [113].

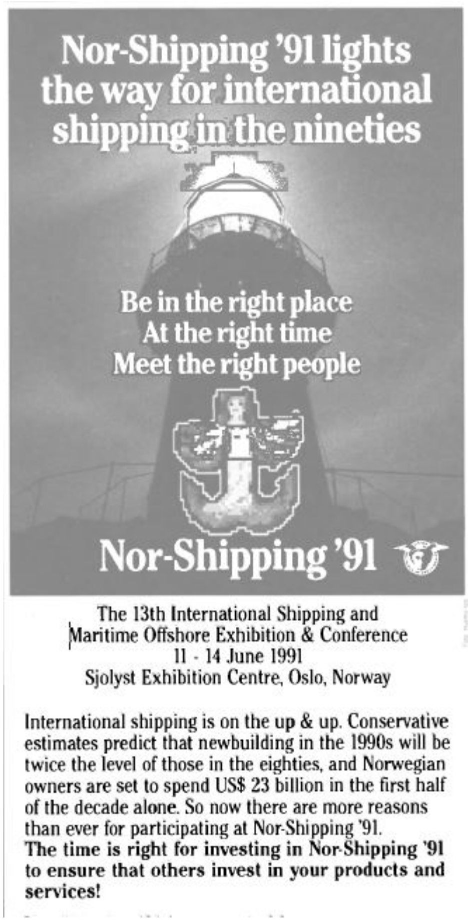


Figure 6. Increased optimism around Norwegian shipbuilding in the early 1990s [114].

In 1993, the Norwegian Parliament started debating the potential use of natural gas as a marine fuel. The local MP from Rogaland showed support for marine natural gas on grounds of environmental benefits and its role in the gasification of Norway [113]. At the same time, Minister of Transport Kjell Opseth expressed support for the natural gas ferry project, but also outlined some safety concerns of using natural gas in ferries [113]. Discussions around the safety of natural gas operations were already well established by 1993 [85,115]. In 1994, natural gas ferries became established government policy, with the creation of the parliamentary 'Energy and Environment Committee-Norway as a Gas Nation' to study the role of natural gas in Norway's future with the aim of using natural gas to increase government revenue, improve environmental conditions, and strengthen Norwegian industry and business [116]. There was growing support for the development of LNG-fuelled ferries rather than compressed natural gas (CNG). LNG started to be linked to areas where LNG was already available, such as Tjeldergodden [117], but there were also arguments stating that some areas are more suitable for CNG (i.e., Rogaland and Hordaland), whilst others are more suitable for LNG (i.e., More og Romsdal and Trondelag) [117]. In addition, during this period, the government started delegating more responsibility to the 'Roads Directorate' with respect to LNG developments: "The Ministry of Transport and Communications has asked the Directorate of Public Roads to report the costs and practical solutions for the conversion of current ferry routes to natural gas operations and what measures are required on the ferry quays" [117].

In September 1994, a government report concluded that, "...ferry gas operation can be considered as safe as operating on conventional fuel" [116]. The Ministry of Transport also established a committee ('Natural gas as a fuel in the transport sector'/Naturgass som drivstoff i transportsektoren') made up of various 'niche' and 'regime' actors [118]. The committee proposed that pilot projects with natural gas ferries should be considered through a 'pilot trial', in connection with the 'strategy to reduce NOx emissions' [118]. On 7th of March 1996, the 'Energy and Environment Committee on Norway as a Gas nation', gave its recommendations to the Ministry of Food and Industry [118].

The recommendations concluded that natural gas is an environmentally friendly fuel viable for ferries, that developing LNG liquefaction facilities will increase maritime opportunities for LNG, and that natural gas is linked to the future of Norway as a 'gas nation' [118]. The conclusions were a commitment to continued development of the use of gas in Norway, with the aim of continuing 'gas-related research' and 'support for pilot projects and development of gas-related equipment' [118].

Several months later, on 14 June 1996, the Transport Committee finalised its work and made recommendations to the 'Ministry of Transport and Communications'. The findings show continued commitment to LNG and persistent 'niche–regime' interactions influencing the regime. The main recommendations [116] were as follows:

1. The Boknafjord option (CNG ferry) for a natural gas ferry development seems to have become less viable due to the uncertainty around CNG safety and apparent unsuitability of the route for LNG operations.
2. An LNG-fuelled ferry should be built and put in operation around Tjeldbergodden, due to existing LNG availability at the location.
3. 'Troll Committee' work by MARINTEK/SINTEF provided confidence that natural gas is as safe as conventional fuels.
4. Previous work on the viability of a natural gas ferry connection in Denmark and existing CNG ferry operations in Canada were used as arguments that natural gas is a safe and mature technology.

Over this period, the Norwegian 'Directorate of Public Roads' (henceforth referred to as the 'Roads Directorate'), in charge of most of the principal ferry connections in the country, was closely involved with the government in researching the potential for natural gas-fuelled ferries. As early as 1993, the Ministry of Transport and Communication requested further research by the Roads Directorate on natural gas-fuelled ferries. It seems that the Canadian CNG experience left a personal impact on the viability of natural gas for Norwegian ferries during this time: "I think the road directorate was central in that, I know that they were on a study trip to Canada in the US to look at vessels operating on CNG...".

The involvement of the 'Roads Directorate' in marine LNG signalled a shift in which the 'regime' took further control in developing the marine LNG niche. As early as 1996, the 'Roads Directorate', publicly announced in its monthly gazette the intention by the government to build an LNG-fuelled ferry in More og Romsdal [119].

The recommendations to build an LNG-fuelled ferry close to Tjeldbergodden were cemented in March 1997, when the Norwegian Government announced the decision to build the LNG-fuelled ferry in More og Romsdal [120]. Funding for the project was allocated in the 'Norwegian Road and Traffic Plan 1998–2007', with the aim of utilizing LNG from Tjeldbergodden [121]. This happened in the wider context of the growing understanding in 1996, from the Ministry of Transport and Communication, that LNG could be quickly made available at Tjeldbergodden by the autumn of 1997 [122]. At the same time, the decision for the construction of the CNG ferry at Boknafjord kept being further delayed, due to the 'complicated' nature of the project [123]. In 1997, the Boknafjord connection was declared not 'practically possible' for utilizing CNG, with further planning assumed under LNG [124]. Due to the unavailability of local LNG, the project lost traction [122].

With respect to the pilot LNG-fuelled ferry, the decision in 1997 started a chain reaction, eventually resulting in the development of the 'Glutra' LNG ferry. Even though the contract for the supply of LNG was signed with More og Romsdal Fylkesbatar (MRF), the regional municipalities and national government seem to have played an active role in promoting the project. The Roads Directorate formed a working group with the aim of delivering the ferry [125]. In 1997, the process of choosing the ferry operator took place. According to Interviewee 31, the decision by MRF to become the operator was a result of a direct negotiation between the company and Norwegian Government authorities: "…later on in 1998 our company made an agreement with the government, to build an LNG propelled ferry called Glutra, delivered in 2000, and that was not a bid system, that was the result of a direct agreement with our company, or rather MRF". The process of ferry constructions and other key regulatory and engineering developments was finalised by the end of 1999, and 'Glutra' began operations in February 2000 [92].

4.3. 1999–2001 NOx Reduction Non-Compliance and Opposition to Gas Power Plants—Political Changes in Norway

The new century began in Norway with two significant 'regime' developments. Firstly, the debate around the usage of natural gas in power plants intensified and resulted in a political crisis. This crisis led to the breakdown of the Norwegian Government and resulted in the long-term political distancing from natural gas as a potential heating source. Secondly, concerns surrounding SOx and NOx were highlighted by the Gothenburg Protocol and associated criticism of Norway from the international community for growing NOx emissions.

The issue of gas-powered plants in Norway was discussed heavily through the 1990s [126,127]. There seems to have been a 'politisation' of natural gas usage in power production, in connection with the debate around Norway's CO_2 emission reduction target at the time [126]. In 1996, a petition opposed to gas-powered stations collected over 100,000 signatures [128]. The petition was part of a wider environmental movement, driven by environmental nongovernmental organisations (NGOs) against potential CO_2 emissions from the new gas power [128]. The debate around the environmental benefits of natural gas for power production led to the resignation of the Bondevik Government in March 2000, resulting in a slowdown in political support for gas power plants [127,128]. This landscape destabilisation of the 'regime' potentially had a positive effect on the adoption of natural gas in ferries. No evidence was found to suggest that similar opposition existed to natural gas adoption within the maritime sector, and potentially the maritime sector provided a more politically neutral route for the utilisation of Norway's natural gas resources.

Secondly, environmental landscape pressures moved the 'regime' towards a broader commitment to air pollution abatement. During the late 1990s and early 2000s, apart from the gas power debate, SOx and NOx concerns continued to be part of the political debate. The adoption of the Gothenburg Protocol in 1999 set a national emissions ceiling for SOx and NOx emissions [23]. Under the Sofia Protocol, Norway committed itself to reducing national missions of NOx to the 1987 levels by 1994 [22]. By the second half of the 1990s, the increase in offshore oil and gas production, and expansion of the transport sector, led to increases in Norway's NOx emissions and contributed to Norway missing its Sofia Declaration NOx reduction targets [129]. Consequently, in 2001, the OECD, in its annual environmental performance review, criticised Norway for not meeting its NOx targets [130].

4.4. 2001–2004 NOx Reduction, Gas Exploration, and LNG-Fuelled PSVs

Following the completion of Glutra, the 'regime' continued taking an active role in embracing maritime LNG. By 2001, Statoil experienced growing pressure to deal with NOx emissions from its gas-powered plants. Statoil and Norsk Hydro began pursuing plans for the development of gas-powered plants in Norway as early as 1994 [131]. During the 1990s, Statoil remained committed to developing gas-powered plants viewing them as an,

"...important business opportunity" [132]. As of 2000, under the political changes that occurred in Norway, the development of the Karsto and Mongstad Power Stations that began in the 1990s was slowed down [133,134].

In 1997, Statoil put into operation the Methanol Plant at Tjeldbergodden [135,136], and during the following 4 years, emissions from Tjeldbergodden continued to grow [137]. By the late 1990s, Statoil was trying to address NOx emissions from its land and offshore installations through offsetting, by using PSVs emitting less NOx [138]. In 2000, Statoil explicitly mentioned Norway's Gothenburg Protocol commitments and said that cutting NOx emissions from maritime vessels might be easier than from land-based operations [138].

Apart from land-based sources, Statoil had significant NOx emissions from its continental shelf offshore facilities [138]. Growing concerns over such emission led the Norwegian Petroleum Directorate to cooperate with the 'Norwegian Pollution Control Authority' through a working group aimed at "...examining measures and costs associated with reducing the emissions of NOx from production installations on the shelf" [131]. The results showed that "...there are several different technologies that can reduce the emissions, but that the costs are generally high and vary considerably from installation to installation" [131]. A solution was seen in developing a "...quota system for NOx emission" [131], which according to the Petroleum Directorate, 'affected' the Ministerial-level thinking on the issue [131]. In June 2001, the Norwegian Government announced that Statoil would contract two new PSVs running on natural gas, stating that Statoil had requested that NOx reductions from the PSVs be considered as 'credits' against its land-based emissions [139].

4.5. 2001–2006 LNG as a Ship Fuel Takes off in Norwegian Ferries—Norwegian Institutional Agency Empowering the LNG Niche

As of 2001, the NOx emission 'landscape pressures' kept growing. In February 2001, discussions began in the Norwegian Parliament around the potential to construct new LNG-fuelled ferries, with a specific emphasis on the desire to construct new ferries for operation in western Norway to reduce locally 'high' NOx emissions [140]. In the context of these developments, Norway issued a new 'National Transport Plan' that directly outlined natural gas as an environmentally friendly alternative fuel for the transport sector [141]. The transport plan confirmed that natural gas used as a fuel would be exempt from fuel taxation. In addition, the transport plan specifically reiterated the decision of the 'Stord and Fitjar Municipalities Council' for the evaluation of the potential for a new ferry connection between Sunnhordland and Bergen, asking the Roads Directorate to evaluate the viability of natural gas as a fuel usage [141].

In 2004, the LNG ferry niche continued to mature. In March 2004, the Ministry of Transport and Communications made the final recommendations for the new 'National Transport Plan' for 2006–2014. An agreement was made 'to implement' NOx emission reduction measures, with a 'particular' focus on the 'ferry sector' [142]. The official text of the 'National Transport Plan' adopted in March 2004 mentioned that 'natural gas ferries' should be, "...continuously assessed in relation to the cost and the possibilities for reducing emissions using conventional technology" [142]. Specific mention is made of the Boknafjord and Bjornafjord ferry connections, saying that tenders for new ferries should be conditional upon natural gas propulsion [142]. By the end of 2004, the Roads Directorate stated that the total number of ferries to be built and operated with natural gas would be five [143]. As can be seen from Figure 7, the decision to build the five new gas ferries gathered significant local media attention in Norway at the time.

4.6. 2005–2008 The NOx fund and LNG Growth—LNG Ferry 'Niche' Is Fully Integrated into 'Regime'

During the 4-year period from 2005 to 2008, the 'regime' in Norway went through a period of increased domestic developments, with construction of new LNG-fuelled vessels. At the same time, new regulations were developed, providing additional financial support for the LNG as a marine fuel 'niche'. The political situation continued to favourably develop, with increasing attention given to NOx emissions from shipping. In March

2005, the 'Norwegian Government' published its renewed environmental policy stating specifically that "About 40 percent of the Norwegian NOx emissions come from domestic shipping and fishing. The analysis shows that the measures for ships and fishing vessels are the most affordable. A significant part of emission reductions should occur in these sectors" [144]. The policy mentions, with reference for Norway's Gothenburg Protocol NOx emission targets, that the Norwegian Government should "Assess whether funding should be granted for NOx-reducing measures on ships and fishing vessels" [144].

Figure 7. Several examples of local media coverage of Fjord1 ferry bid (Clockwise translation of the titles: 'Fjord1 won gas ferry routes', 'Fjord1 won bid for gas ferries', 'A big day for Fjord1', and 'Fjord1 won battle for gas ferries').

From a 'landscape' perspective, natural gas production continued increasing, until the global economic slowdown in 2008–2011. In this climate of growing domestic gas production, it seems likely that policies, which would support increased use of domestic gas, would also be favoured. In March 2006, the 'Norwegian Pollution Control Authority' published a study analysing the costs of NOx-reducing measures for domestic shipping, land-based sources, and onshore industry. The report concluded that the least expensive measures for NOx reduction exist in fishing and domestic shipping [145,146]. Under such circumstances, negotiations and parliamentary debates around the NOx tax were held. On 12 May 2006, an agreement was reached to set a tax on NOx emissions, including maritime shipping from 1 January 2007 [147]. During the following several months, discussions took place over whether to modify the tax into a 'NOx fund' or not. On 28 September 2007, the final decision to create a 'NOx fund' was made [148]. The fund entered into force on 1 January 2008, through an 'Environmental Agreement' signed between the Ministry of Climate and Environment and 14 industry NGOs [149]. At the same time, the Norwegian Government and Roads Directorate continued promoting the uptake of LNG in Norwegian coastal ferries, with the aim of issuing tenders for four new gas ferries by 2009, on the road route between Stavanger and Bergen [150].

4.7. 2008–2012 Boom in Norwegian LNG-Fuelled Ships

During 2008–2012, a significant development boom in the marine LNG industry occurred in Norway. Following the establishment of the Norwegian NOx fund in 2008, the following 5 years saw a steady rise in the number of orders for LNG-fuelled vessels. Initially, most orders were for shortsea ferries and PSVs, but over time, orders for different types of ships for operation in Norway started being made (Figure 8). This apparent niche 'accumulation' [55] accelerated the transition of the Norwegian 'regime' to LNG.

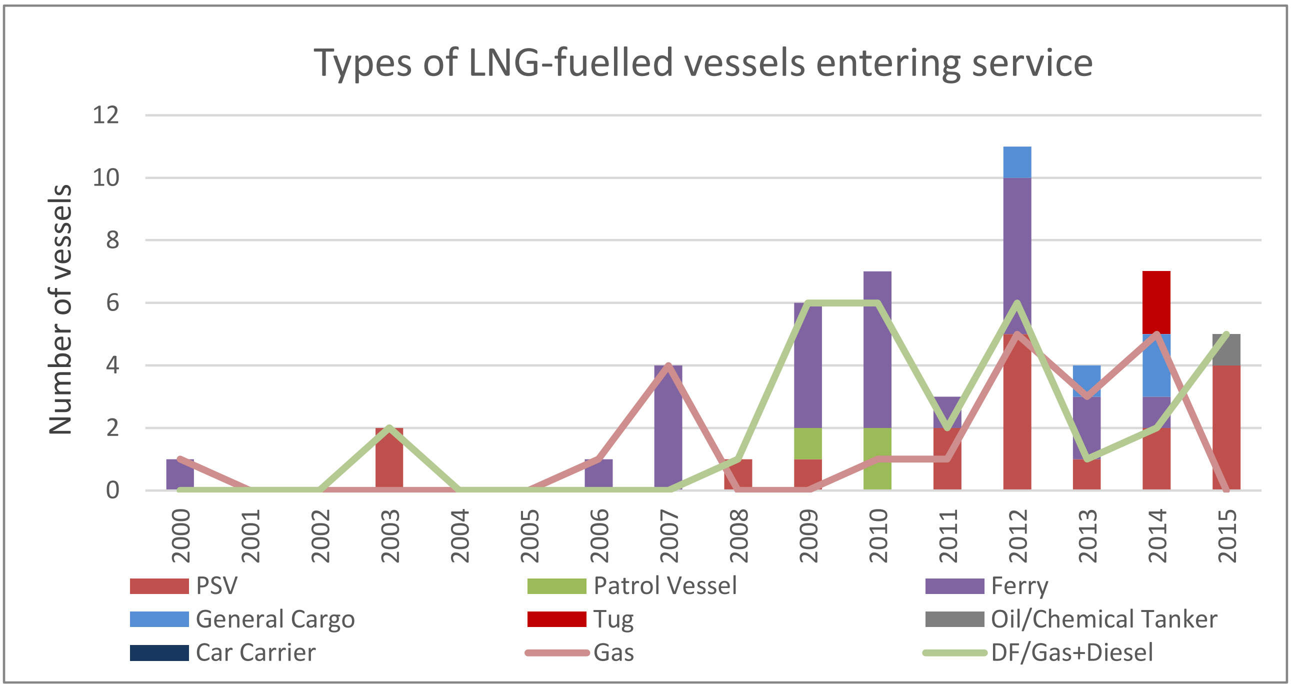


Figure 8. Norwegian LNG-fuelled ships entering service annually (Ships whose main area of operation is Norway).

During 2008 and 2009, the development of LNG as a marine fuel in various 'niche' segments of the Norwegian maritime industry diversified significantly, with several new projects. Firstly, two additional PSV vessels powered by LNG came into operation [151,152], seemingly driven by requirements from Statoil and Total [151,153,154]. Apart from developments with respect to PSVs, ferry orders also continued, with the Roads Directorate issuing more tenders specifically requesting LNG-fuelled ferries.

The established industry player Fjord1 won these tenders in a great majority of cases. However, other actors such as Tide Sjo also won contracts for LNG-fuelled ferries [153]. Most ferries benefited from financial support from the Norwegian NOx fund. During the period 2008–2012, at least 11 LNG-fuelled ferries entered operation in Norway, as a result of tenders issued by the Roads Directorate [142]. All these tenders had a specific requirement for the ferries to use gas as a fuel. These 11 ferries formed over 40% of the total LNG-fuelled vessels entering operation in Norway over this period. Most of the ferries were built under two tenders awarded to Fjord1 [155] and Torghatten Nord AS [156] in 2007 and 2009, respectively.

A push for LNG vessels was not limited to PSVs and the ferry industry anymore, but there was a diversification of niche segments in which LNG as a marine fuel was implemented. In 2006, the first offshore patrol vessel to be powered by LNG was ordered [157]. and was followed by two more sister vessels in 2010 [158].

At the 'regime' level, only minor changes concerning LNG-fuelled vessels occurred during 2008–2012, but destabilising 'landscape' pressures of GHG emission concerns started accumulating. In 2009, the Norwegian Government presented a new National Transport Plan for 2010–2019, with one of the key priorities given to "More ferry capacity and improved services" as well as "New vessels for the Norwegian Coastal Administration" [159]. The plan also called for a reform that would take place in 2010, resulting in the decentralisation of 77 national ferry connections to local and municipal authorities. It is interesting to note that unlike its predecessor, the new agreement put a higher emphasis on GHG emission reductions, with the aim of targeting reductions in the transport sector [159].

4.8. 2013–2015 Slowdown in LNG Orders and Transition to Batteries

Based on the information obtained in this study, 2008–2012 can be considered as the golden period of Norwegian marine LNG developments, based on vessel deliveries (Figure 9). However, the period from 2013 to 2015 saw a slowdown in LNG uptake with decreased support from LNG tenders. From a positive perspective, diversification of the marine LNG 'niche' outside of the ferry segment was occurring. In 2012, the first general cargo vessel fuelled by LNG was delivered [160], followed by three further cargo vessels during 2013–2015 and other LNG-fuelled vessels such as tugs and a chemical tanker were also delivered. The vessels were intended for operation in Norwegian coastal waters or emission control areas (ECAs) and were supported with funding from the NOx fund [161]. The tugs were ordered for a charter to Statoil [162]. Rolls Royce, the tug engine manufacturer, heralded them as "A milestone in green tug Development" [162]. In 2013, Norway allowed the bunkering of LNG-fuelled passenger ships with passengers on board and without requiring the permission of the Norwegian Directorate for Civil Protection (DSB) [163].

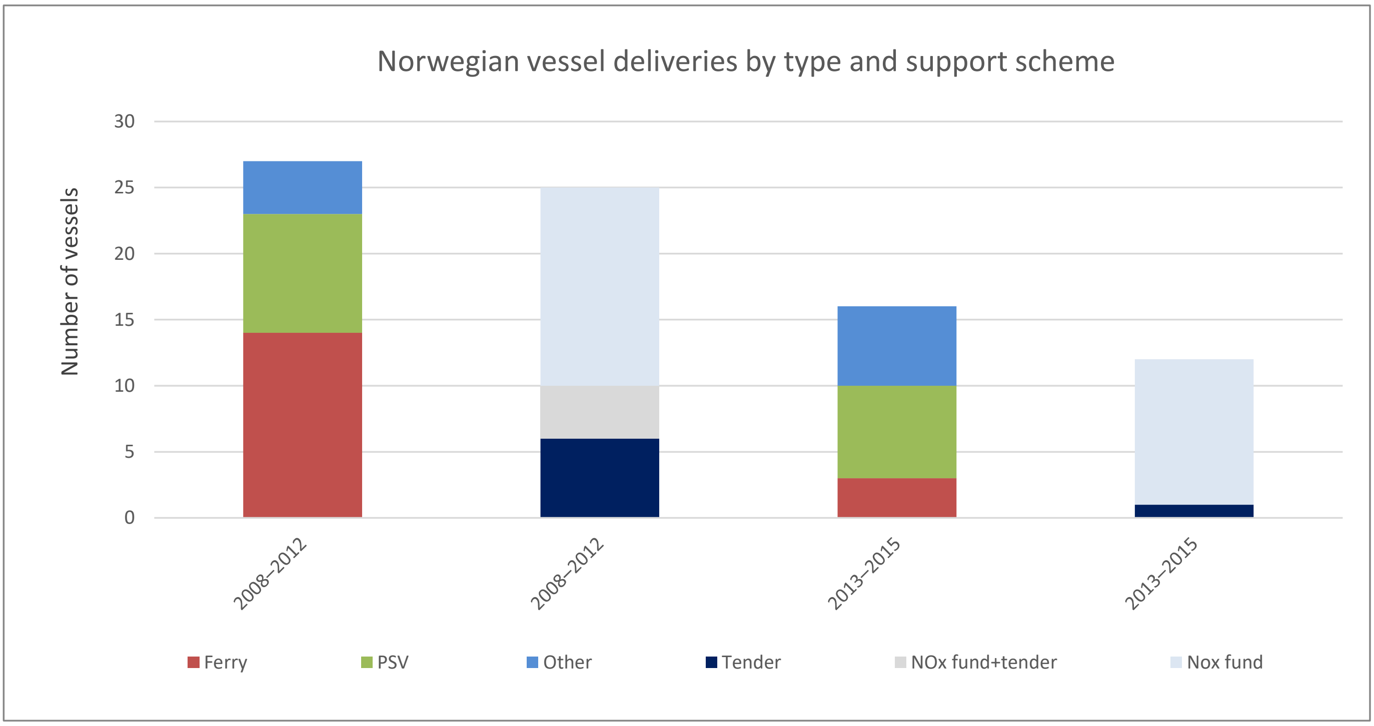


Figure 9. LNG-fuelled vessels delivered in Norway (Analysis based on several sources of information prepared for this study, including DNV GL [164] and Norwegian Business Sector NOx fund [165]).

However, the overall uptake of LNG-fuelled vessels levelled off and previous projections of continued growth in the uptake of LNG as a marine fuel did not come to fruition. This levelling off of growth is difficult to attribute to a single 'regime', 'niche' or 'landscape' factor, but it seems that several factors were in play at the same time. Three factors in particular could have played key a role in the slowdown of the uptake of LNG as a marine fuel in Norway. These factors are as follows:

1. Landscape—Drop in crude oil prices making LNG comparatively less competitive as a fuel.
2. Landscape—Global economic crisis and drop in demand for new vessels.
3. Niche—Development of 'cleaner' alternatives to LNG from Norwegians shortsea ferries, coupled with 'Landscape' pressure of growing GHG emission concerns surrounding LNG

As this is not a quantitative study, or a statistical analysis, ascertaining the exact causal relationship between some of these factors could be quite difficult. Factors 1 and 2 in particular seem to have occurred at the same time and could have had a potential impact on the marine LNG niche. Factor 1 was mentioned by three interviewees (19, 28, and 35) as a potential factor which could have played a role in the slowdown in the uptake of LNG as a marine fuel. Interviewee 35 states with respect to this, "...and then the crack in the oil price came and you had the reality that LNG was not anymore cheaper than diesel fuel, at least in the short to medium term, and the interest totally dropped".

This explanation corresponds well with previous studies [12,166], which predicted that a considerably more favourable price differential between LNG and marine diesel oil (MDO) would have to exist for rapid LNG uptake than what was observed. Similarly, other academic work [44] also shows a close correlation between the MDO/LNG price differential and the potential uptake of LNG. However, any such explanation has to be observed critically, as such explanations are counterfactual. A similar statement could be made for Factor 2. The economic crisis of 2008 and the lowering of oil prices in 2013 did impact Norway and according to the OECD [167] had a negative impact on Norwegian shipbuilding, particularly on the lowering of PSV and other offshore vessel orders, which could have, by extension, affected LNG-fuelled ship orders. However, ascertaining to what extent it could have been responsible for the drop in the uptake of LNG-fuelled vessels is difficult.

The evidence at hand and the apparent correlation between the slowdown in uptake of LNG-fuelled vessels, with a price drop in MDO prices (Figure 10) and the global economic crisis, seem to imply a certain causal relationship, at least implicitly. However, establishing explicitly to what extent previously projected high LNG uptake rates (i.e., up to 1000 ships by 2020) were not realised because of Factors 1 and 2 would require further empirical research, beyond the scope of this study. In addition, Factor 3 was also expressed by four interviewees (27, 29, 31, and 35) as playing an important role in the slowdown of the uptake of LNG as a marine fuel in Norway. Interviewee 27 says, "Yeah, that has been, really large change ..., amm... and the LNG, previously before that it has been, you have the LNG story which has been made, going on the greenhouse gas emissions have been part of it".

The principal difference between the periods from 2008 to 2012 and 2013 to 2015 is the radical drop in the number of LNG-fuelled ferries entering service. Even disregarding any impact of Factors 1 and 2, the other segments of the industry seem to have continued ordering LNG-fuelled vessels at a steady rate. Consequently, the significant drop in LNG vessel delivered over this period is potentially due specifically to a decline in ferry orders.

Out of 17 ferries built in Norway with LNG capabilities during 2008–2015, 11 had tenders that specifically required the usage of LNG as a fuel. Thus, it seems that the apparent lack of new tenders for LNG-fuelled vessels significantly contributed to the overall drop in new LNG developments. The principal reason seems to be the lack of support for LNG in Roads Directorate tenders from 2014 onwards. Furthermore, in December 2014, the Norwegian Parliament asked the Norwegian Government to, "...ensure that all upcoming ferry tenders have requirements for zero-emission technology (and low-emission technology) when the technology dictates this" [168]. This decision guaranteed that all future official Roads Directorate tenders would have to be near-zero emissions, even though the decision itself did not initially mention whether LNG could be counted into such technologies or not [168]. However, following this decision, only two further LNG-fuelled ferries were ordered up to 2015, and these were not through the government tendering process.

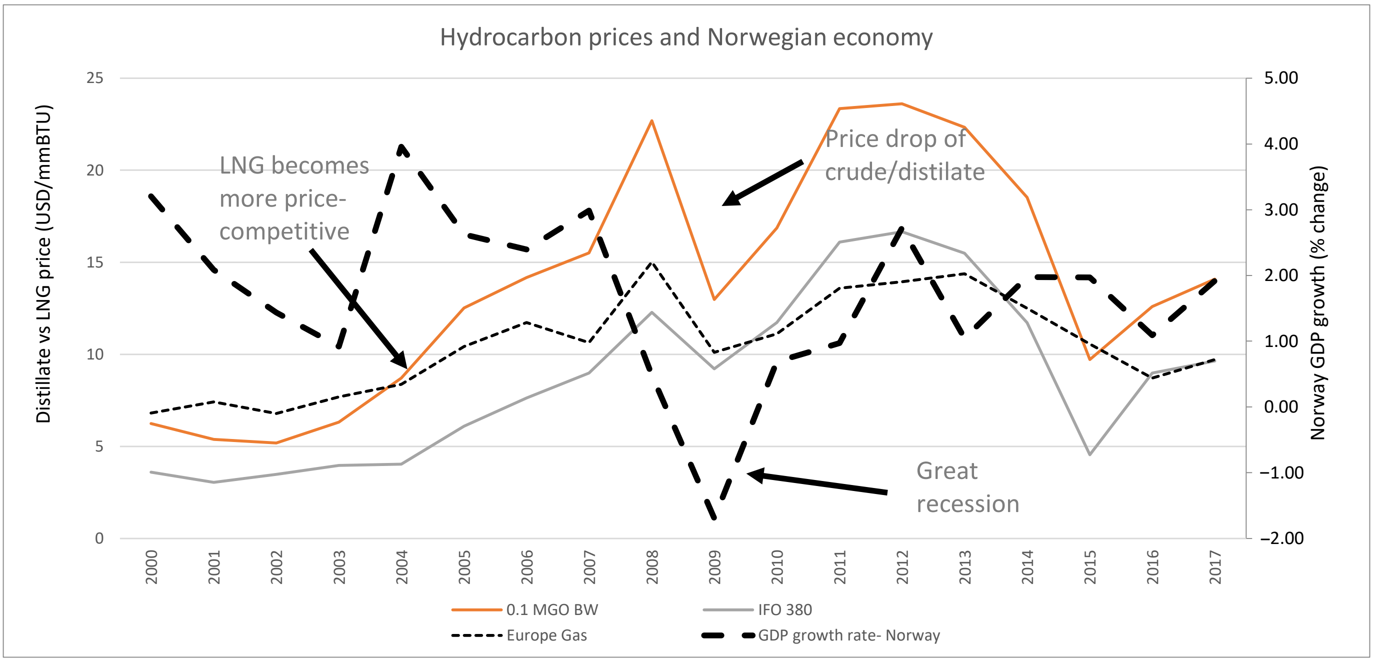


Figure 10. Distillate vs. LNG price and Norway GDP growth (Distillate prices are from DNV GL [164]; gas prices are from the *BP World Energy Review* [169] and are an average of average German natural gas import price, UK Heren NBP index, and Netherlands DA Heren Index; natural gas price has an average of USD4/mmBTU liquefaction cost added (based on DNV GL figures of liquefaction costs ranging from USD 3 to 5/mmBTU), and Norwegian GDP growth rates are from the World Bank [170]).

Other potential drivers that might have contributed to the drop in LNG ferry orders, such as the economic crisis and/or market saturation, seem to have been considerably less relevant. During 2008–2015, the number of shortsea ferries coming online in Norway remained steady, but the number of ferries fuelled by LNG continued to decrease. Thus, it seems unlikely that LNG tenders were not issued simply due to market saturation. Secondly, the availability of the NOx fund to offset any capital expense (CAPEX) premium on LNG new builds further weakens the argument that financial challenges were the sole driver. Furthermore, LNG taxation in Norway did not change over this period, with LNG for sea transport remaining exempt from the CO_2 tax until 1 January 2018 [171].

Consequently, the removal of tendering options in 2014 for LNG seems to have had a considerable negative effect on LNG uptake in Norway (Figure 11). This 'regime' shift started being apparent in 2013, when the 'National Transport Plan 2013–2023' was published, showing support for LNG, but also discussing alternatives such as electricity on grounds of lower GHG emissions: "Norway is the world leader in the use of LNG, liquid natural gas, as a marine fuel. LNG is a good alternative to heavy oil. . .For ferries and speedboats, there are many connections where both sailing patterns and instruments can be adapted for use of alternative fuel—including electricity" [172].

In addition, new 'niche' pressures were occurring as well. The potential to develop a battery electric ferry began with a government decision in 2010/2011, to create the ". . .most energy and environmentally efficient ferry to the national road service" stating that ". . .electrically operated ferry or ferry with biofuel may be relevant" on the Lavik—Oppedal route [172]. The ferry development process took several years and eventually resulted in the creation of the first battery electric ferry in the world, the 'Ampere' [173]. The development of the 'Ampere' implies a general change of opinion within the Roads Directorate and the Norwegian 'regime'. According to Interviewee 30, a general heightened perception of GHG concerns coupled with battery innovations drove this process.

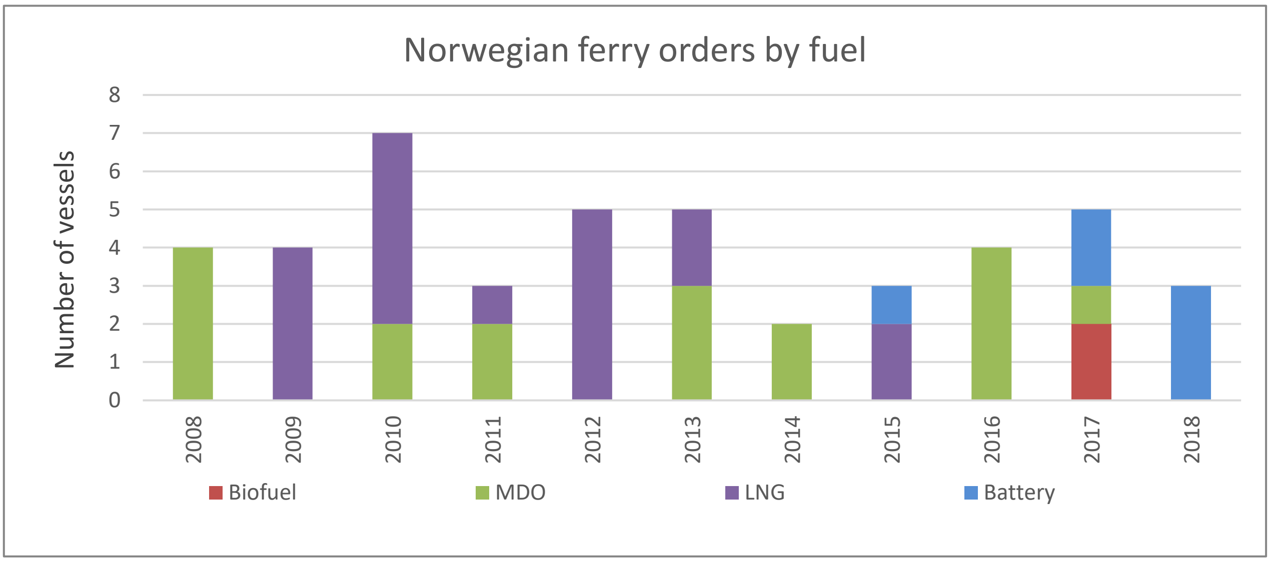


Figure 11. Shortsea ferries coming into operation in Norway (Analysis for this paper based on underlying data from DNV GL [164]).

Shortly after the 'Ampere' came into operation and after the decision to change the tendering process, more intense discussions began about how Norway could deal with its GHG reduction commitments ahead of COP21. In February 2015, the Norwegian Parliament prepared its 'emission obligations for 2030' that stated a commitment to limit global warning to "...at least a 40 per cent emission reduction in 2030 compared with 1990" [144]. This commitment was followed in November 2015 with further political support from the Norwegian Parliament for the 'promotion' of 'zero-emission' technology being used in future ferry tenders and to determine, "...which ferry connections are suitable for operation using clean electricity" [174]. These political commitments signalled the end of LNG use in Norwegian ferries and the start of a new transition, the battery electric transition, driven by GHG concerns, rather than NOx.

5. Discussion

The previous section showed that from an MLP perspective, a complex picture of marine LNG developments in Norway can be painted over all MLP levels. The marine LNG niche developed first in Norway where it benefited from 'passive' shielding, with landscape, regime, and niche interactions beginning as early as the mid-1980s, growing in intensity during the 1990s with political developments driving the destabilisation of the existing HFO regime and strengthening the LNG niche. Over time, this strengthening led to a complete reorganisation of the Norwegian ferry sector, where the LNG regime became dominant. However, this reconfiguration was followed by another transition to batteries in the 2010s.

5.1. Landscape

Destabilising landscape pressures, such as depleting oil reserves in the 1980s and 1990s, with a switch from oil to natural gas production and LNG exports, provided more incentives for LNG over HFO. With respect to natural gas, the Norwegian energy regime responded by steadily increasing gas production and exports during the 2000s and 2010s. The 1980s saw growing SOx/NOx emission concerns, continuing into the 2010s, with enforcement of IMO ECAs and NOx Tier III. In the 1990s, these forces were the strongest. Such pressures had a destabilising effect on the socio-technical regime within Norway. Another key landscape force was changing natural gas and LNG market pressures. The natural gas markets started having a destabilising effect in the 1980s as environmental regulations became more stringent. In the 1990s and 2000s, favourable LNG prices further destabilised the HFO regime. This development was somewhat hampered in the late 2000s by the global economic crisis that made distillate fuels comparatively more appealing than LNG. GHG concerns in the 2000s and 2010s initially destabilised the maritime regime making it more aligned to the marine LNG niche. However, as GHG concerns intensified, LNG methane slip concerns became more pronounced and other more sustainable niches increased in strength, leading some regime actors to gradually turn away from LNG. These issues tended to be somewhat overlooked in other empirical studies of the Norwegian LNG niche [6,26].

In Norway, natural gas field discoveries in the 1980s also led to regime destabilisation. This occurred in combination with other medium-term landscape changes such as the shipbuilding crisis which affected Norway in the 1980s and 1990s. The crisis exposed the need to reorient shipbuilding to specialised vessels, such as PSVs and ferries. The shipbuilding crisis negatively affected Ulstein Bergen engine manufacturing profits by destabilising the maritime industry and supporting its reorientation towards gas engine manufacturing. In the mid-2000s, the election of pro-environmental parties and the associated growth in environmentalism seem to have energised the Ministry of Environment to support the establishment of the NOx fund.

5.2. Regime

Some key Norwegian LNG developments which affected the regime during the case study period are visualised in Figure 12. Norway experienced regime destabilisation during the 1990s and 2000s with respect to growing concerns surrounding SOx/NOx emissions and in the 2010s with respect to GHG concerns. The 2000s also saw a gradual reorientation of the regime towards a higher appreciation of environmental concerns from SOx/NOx emissions. By the end of the decade under favourable landscape forces, elements of the regime began perceiving LNG as a potential alterative to HFO. However, the economic crisis and falling crude oil prices in the 2010s stabilised the HFO regime by making LNG vessels less profitable and generally slowing down construction of new vessels. During the 2010s, there seems to have been a general diversification of opinions within the regime concerning the long-term viability of LNG.

Landscape forces played an especially strong role in destabilising the regime and combined with niche pressures from shipping, engine manufacturers, and the gas industry to develop a strong marine LNG niche. The strength of these can be attributed to a combination of particularly high NOx emissions from coastal shipping and their environmental effects, in combination with a strong political desire to develop domestic shipbuilding, LNG supply, and natural gas expertise. The Norwegian marine LNG development timeline spanned 3 decades and included several 'milestones' such as the political decisions in the early 1990s to develop LNG as a viable fuel, the launch of Glutra in 2000, and the Roads Directorate decision to issue tenders for LNG-fuelled ferries in the 2000s.

In the 1980s and 1990s, first niche–regime–landscape interactions began to take shape. The regime experienced significant changes in the late 1980s, primarily destabilised by the changing oil and gas market situations and growing environmental concerns. The period from 1996 to 2005 was characterised by the growth of niche–regime interactions and a slow development of a niche, principally through research and development (R&D). The period from 2006 to 2015 saw the greatest expansion. This period was characterised by the ongoing landscape destabilising regime forces, these primarily being SOx/NOx concerns and by the 2010s, also GHG concerns. In particular, the social costs of NOx, because of its possible effects on human health, were seen as being quite high, something which has been paralleled by other studies on transport and NOx globally [19,21]. Both types of concerns had a destabilising effect on the regime, but the former destabilised the regime in such a way to make it more appealing to LNG, whereas the latter, initially supported LNG, but in later years, GHG emissions worked against LNG primarily due to methane slip issues. The key drivers for the Norwegian LNG niche were environmental concerns and natural gas utilisation issues, primarily driven by the Norwegian political establishment. This contrasts with other empirical work on European natural gas drivers which outlines that the key drivers for natural gas were consumers [26]. Consumers played a role in the Norwegian regime, but that role was not as prominent. Where consumers did possibly play a role was through the electorate shaping the political narrative around environmental issues.

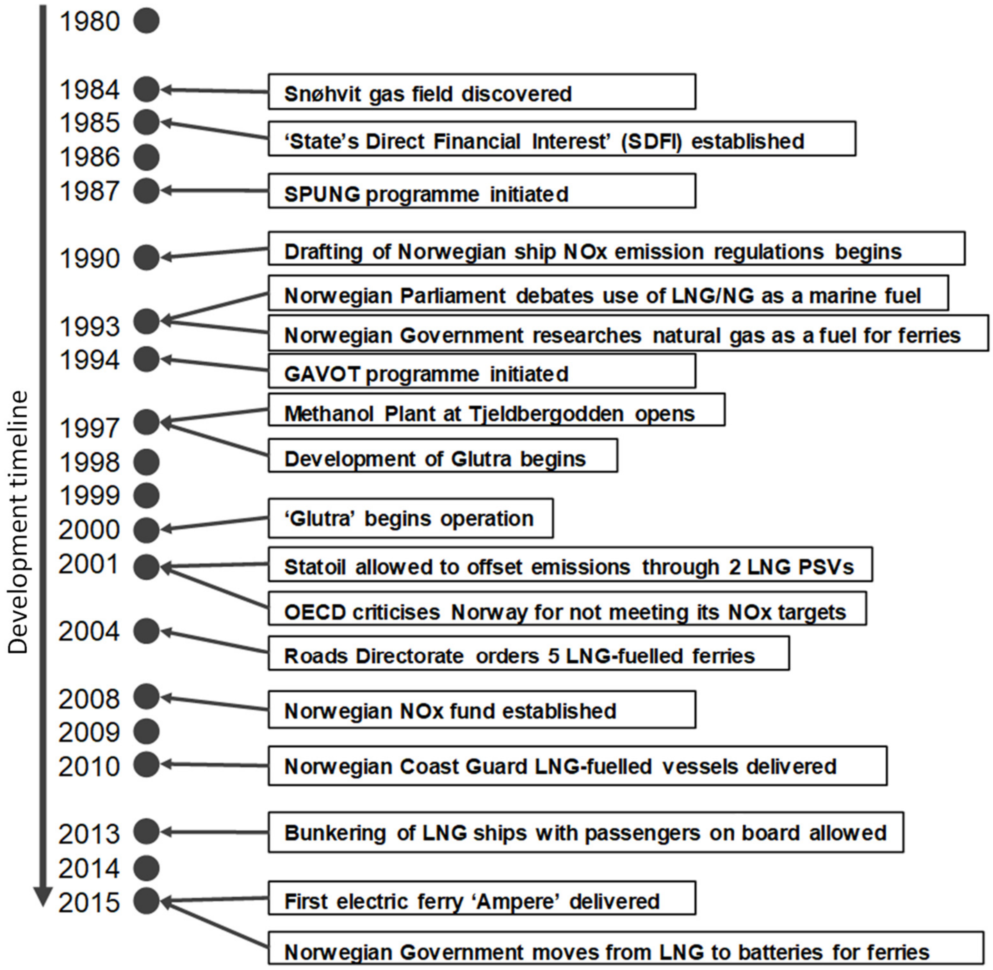


Figure 12. Timeline of Norwegian developments relating to LNG as a marine fuel.

5.3. Niche

In Norway, the marine LNG niche benefited from 'passive' shielding due to a significant number of shortsea ferry routes and a large shortsea shipping sector. In such an environment, the passenger ferry industry by transferring part of the cost to the consumer and oil and gas industries by way of premium for LNG PSVs to avoid any more stringent regulations, provided a steadily revenue stream for the development of LNG. Under such passive niches, active niches were also developed by the Norwegian Government through support from various funding programmes, initially for R&D (i.e., SPUNG, GAVOT), then pilot projects and R&D (i.e., Glutra ferry and NATURGASS), and finally for full-scale deployments (i.e., via the NOx fund). This early-stage development was highly relevant in creating the starting conditions for the LNG niche, and previous empirical work has offered limited understanding of the political forces underpinning it [6]. Additional niche growth came in the mid-2000s, when the government started requiring that new ferry tenders require natural gas propulsion. Other empirical work regarding the Norwegian LNG niche [27] supports the broader developments around the policy agenda but does not go into detail around the underlying drivers. However, in general, it is aligned with the postulation that local niche development was happening in parallel with regional

ECA developments, something that from a niche perspective is also supported by other empirical work [6,19].

From a longitudinal narrative of how LNG as a marine fuel developed from 1985 to 2015, LNG developments can be divided into four distinct periods:

- 1985–1999—LNG niche begins to take shape:

This period is characterised by Norwegian regime developments. The regime was destabilised under landscape SOx/NOx concerns related to environmental degradation and human health, the shipbuilding crisis, political changes, and the growing domestic natural gas industry. Initially 'passive' and later 'active' shielding facilitated the marine LNG niche establishment. Niche developments occurred through R&D into gas engines, gas-fuelled ferries, and bunkering technology research. The period ended with Glutra, the first pilot LNG-fuelled ferry.

- 2000–2007—Scaling up of the Norwegian niche under changing regime circumstances:

This period is characterised by further destabilisation of the Norwegian regime under continuing NOx concerns, increasing environmental pressures, and growing pressures from a strengthened LNG niche. The Norwegian regime reorients towards the niche, and the Roads Directorate issues tenders for LNG ferries. The period ends with the establishment of the Norwegian NOx fund, signalling strong alignment between the LNG niche and the regime.

- 2008–2011—Norwegian niche strengthening:

This period is characterised by landscape forces surrounding SOx/NOx emission pressures and favourable natural gas prices, driving a destabilisation of the regime. This destabilisation opens opportunities for the marine LNG niche to become established. R&D and network formation around LNG as a marine fuel also occur with funding initiated for marine LNG R&D.

- 2012–2015—LNG niche growth, regime reorientation, and slowdown:

This period is characterised by continuing SOx/NOx landscape pressures and growing GHG pressures destabilising the regime, but these are countered by regime stabilisation from the global recession and low crude oil prices. Under such circumstances, the marine LNG niche continues to expand, but at a slower pace. This slowdown is further accentuated by growing GHG concerns around LNG methane slip damaging the niche and promoting other 'more sustainable' niches. The strongest example comes from battery-powered ferries in Norway. This is in line with other empirical work performed on the Norwegian ferry LNG niche [27].

6. Conclusions

The main objective of this study was to understand the socio-technical adoption dynamics of LNG as a marine fuel in Norway between 1985 and 2015 and what lessons can be learnt from this process for other alternative fuels. In order to accomplish this objective, rich sources of documentary evidence from news reports, parliamentary briefing, white papers, and technical magazines were collected and triangulated with interview findings from key actors involved in the process of LNG adoption at the time. The MLP heuristic was applied to the analysis to code the raw data and prepare the findings. The MLP framework provided a valuable tool in framing data collection, in formatting the analysis, and in the conclusions.

The main findings of the study outline that LNG development as a marine fuel in Norway was a complex process driven by socio-economic and socio-political forces, often going beyond shipping, and influenced by a variety of environmental factors. The discussion section outlined that the process of LNG adoption in Norway unfolded through eight distinct phases driven by a combination of initial geopolitical concerns and changes in the shipbuilding industry with the desire to turn Norway into a 'gas nation', followed by growing NOx emission concerns from Norwegian coastal ferries, combined with a growing actor network of stakeholders interested in developing domestic Norwegian engine manufacturing and finally being slowed down by growing GHG emission concerns from gas-fuelled vessels in the 2010s.

In understanding what lessons LNG adoption can give, especially to help to shape the understanding of future fuel transitions such as that of hydrogen-derived fuels, the main findings are as follows:

- Support from incumbent actors—The role of incumbent actors such as well-established shipowners, policy actors (i.e., Norwegian ministries and maritime policy executives), and established LNG producers was key in supporting the narrative around the possible success of LNG as a ship fuel to the public and to possible sceptics. This was especially true when it came to issues of safety, and parallels can be drawn with current developments of fuels such as ammonia. The relevance of incumbents is also supported by other research on ammonia adoption [175].
- Bunkering infrastructure—The chicken and egg problem of supply and demand of the fuel was critical in the early years of the transition. The ability to position early ferry routes close to existing LNG supply and non-maritime demand clusters helped to spearhead the transition. In this sense, geography can play an important role in positioning where the transition begins.
- Niches—Finding industry segments which can be early adopters was key. In the case of LNG, this was the shortsea industry, ferries, or segments that have stable long-term charters useful in guiding the early stages of a transition.
- Hybrid technologies—Development and usage of technologies which can run on multiple fuels, such as dual fuel engines, were key in alleviating 'chicken and egg' concerns.
- Institutional modifications—Fuel transitions include institutional modifications that would alleviate the price difference with existing fuels. In the case of LNG, the NOx fund played a key role in combination with specific tenders for routes to bridge adoption challenges during the early stages of the transition.

When thinking of future fuel transitions, the case of LNG in Norway shows that future fuel transitions will likely require industry reorientation, development of new protective spaces, and alignment of political and industry agendas and can be supported by geographic proximity factors. In these processes, strong incumbent actors will play a key role. Similarly, for alternative fuels, such as hydrogen and ammonia, the role of building strong safety narratives and strategically scaling up maritime supply with dedicated policy support networks will likely be key.

There are several limitations of this analysis which should be considered. Firstly, as this is a single qualitative technological case study, even though several inferences can be drawn from it for adoption dynamics of other marine fuels, each fuel will be different and such comparisons should be made with caution. Secondly, whilst Norway can be considered a unique case study due to its societal, geographic, and economic conditions, it is not a given that the same processes which took place in Norway can be directly transposed to other countries or regions. However, this case does provide evidence that uniquely positioned regions or countries could spearhead an alternative fuel transition. Thirdly, even though the 41 interviews (Appendix A) were carried out in a manner which ensured that a wide variety of different perspectives and voices were represented, a different sample of interviewees could have possibly put emphasis on a different range of driving forces.

Future work should look at in more detail what could be the most appropriate conditions for hydrogen-derived fuel adoption by building on the work outlined in this paper. Examples could be to understand what the role of incumbents could be in driving the adoption of hydrogen-derived fuels and what institutional modifications can be made nationally to support this process.

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Abbreviations

Abbreviation	**Meaning**
CAPEX	Capital Expenditures
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
COP	Conference of the Partis
DNV	Det Norske Veritas
DSB	Norwegian Directorate for Civil Protection
ECA	Emission Control Area
EPSRC	Engineering and Physical Sciences Research Council
GAVOT	Gas Research-Products and Services/Gassforskning—varer og tjenester
GDP	Gross Domestic product
GHG	Greenhouse Gas
HFO	Heavy Fuel Oil
IEA	International Energy Agency
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
LNG	Liquified Natural Gas
MARINTEK	Norwegian Marine Technology Research Institute
MDO	Marine Diesel Oil
MLP	Multilevel Perspective
MMBTu	one million British thermal units
MP	Member of Parliament
MRF	More og Romsdal Fylkesbatar
NG	Natural Gas
NGO	Nongovernmental Organisation
NOU	Norwegian Official Report/Norges offentlige utredninger
NOx	Nitrogen Oxides
NTNF	Royal Norwegian Council for Scientific and Industrial Research/Norges Teknisk-Naturvitenskapelige Forskningsråd
NYMEX	New York Mercantile Exchange
OECD	Organisation for Economic Co-operation and Development
OPEC	Organization of the Petroleum Exporting Countries
OPEX	Operating Expenditures
PM	Particulate Matter
PSV	Platform Supply Vessel
R&D	Research & Development
SDFI	State's Direct Financial Interest
SDG	Sustainable Development Goal

Abbreviation	Meaning
SFT	Norwegian Ministry of Environment, the Pollution Control Authority
SINTEF	Foundation for Industrial and Technical Research/Stiftelsen for industriell og teknisk forskning
SOx	Sulphur Oxides
SPUNG	State programme for utilisation of natural gas/Statlig programme for utnytting av naturgass
UK	United Kingdom
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
UNSDG	United Nations Sustainable Development Goals
WCED	World Commission on Environment and Development

Appendix A

Table A1. List of anonymised interviewees.

Interviewee	Anonymised Description
Interviewee 1	Senior figure in EU maritime LNG policy
Interviewee 2	Senior figure in EU maritime LNG policy
Interviewee 3	Senior figure in EU/IMO maritime GHG debates
Interviewee 4	Senior LNG technical expert
Interviewee 5	Senior maritime economics expert
Interviewee 6	Senior figure in Danish LNG developments (Administration)
Interviewee 7	Senior figure in Dutch LNG developments (Port Authority)
Interviewee 8	Senior figure in Dutch LNG developments (Shipowner)
Interviewee 9	Dutch IMO Delegate
Interviewee 10	Senior project manager for LNG projects in Netherlands
Interviewee 11	Dutch IMO Delegate
Interviewee 12	Senior figure in Belgian LNG developments (Port Authority)
Interviewee 13	Senior figure in Finnish LNG developments (Port Authority)
Interviewee 14	Senior figure in Estonian LNG developments (Shipowner)
Interviewee 15	Senior figure in Swedish LNG developments (Shipowner)
Interviewee 16	Senior figure Norwegian LNG bunkering developments
Interviewee 17	Senior figure in Norwegian LNG bunkering developments
Interviewee 18	Senior figure in Norwegian LNG developments (Shipowner)
Interviewee 19	Senior LNG proponents (Industry Association)
Interviewee 20	Swedish IMO Delegate
Interviewee 21	Swedish IMO Delegate
Interviewee 22	Danish IMO Delegate
Interviewee 23	Finnish IMO Delegate
Interviewee 24	Senior figure in Danish LNG developments (Shipowner)
Interviewee 25	Senior figure in Danish LNG developments (Industry Association)
Interviewee 26	Senior figure in Norwegian LNG developments (Shipowner)
Interviewee 27	Executive in a Norwegian maritime decarbonisation NGO
Interviewee 28	Senior figure in Norwegian LNG bunkering developments
Interviewee 29	Senior figure in Norwegian LNG engine developments
Interviewee 30	Senior figure in the Norwegian Public Roads Directorate
Interviewee 31	Senior figure in Norwegian LNG developments (Shipowner)
Interviewee 32	Norwegian IMO Delegate
Interviewee 33	Senior figure in Norwegian LNG bunkering developments
Interviewee 34	Senior executive in a Norwegian Shipyard
Interviewee 35	Senior figure in 'Norwegian NOx fund'
Interviewee 36	Senior figure in Finnish LNG developments (Shipowner)
Interviewee 37	Senior executive at Netherlands Maritime Technology
Interviewee 38	Senior executive at the Research Council of Norway
Interviewee 39	Senior figure in Flemish Government (Regulator)
Interviewee 40	Senior figure in Croatian LNG developments
Interviewee 41	Senior figure in German LNG developments

Appendix B

Interview protocol—Example
Interview instructions:
Pre-recording:

1. **Give short introduction to research and importance of interviewee:**

   'This research project aims to understand how has the maritime industry in northern Europe developed and changed since 1985 with respect to different socio-economic and political pressures.

   Furthermore, the aim of this research project is to understand how the use of LNG (liquefied natural gas) as a ship fuel evolved, changed and has been modified to meet the needs of the shipping industry'.

2. **Give short explanation of interview procedure:**

During recording

1. **Start recording**
2. **Ask for permission:**

   'I am recording this interview for the purposes of this research project; is that OK with you?'

3. **State for the record:**

   'I am conducting an interview with xxx, xxx; the date is xxx, and the location of the interview is xxx'.

4. **Interview Questions:**

INTRO—OPENING QUESTIONS

1. Can you tell me a bit about your own background and role at xx?
2. Can you tell me what in your opinion were the main changes the xx (area of interest) experienced over the previous 30 years?

Probe: What about the Norwegian maritime industry?
ACTORS AND SOCIAL GROUPS—REGIME AND NICHE

3. Who in your opinion have been the main actors who shaped the Norwegian maritime industry?
4. Moving on to environmental issues, how has the Norwegian shipping industry's view on GHG and SOx/NOx emissions from ships evolved since the 1980s?

Probe: What about GHGs?

5. Can you identify specific pressure groups that exerted pressure on the industry with respect to choice of fuels?

RULES AND INSTITUTIONS—REGIME AND LANDSCAPE

6. What have been the main regulatory developments with respect to choice of fuels that affected the industry since the 1980s?
7. How did the industry respond to this changing regulatory landscape?

ACTORS AND TECHNOLOGIES—REGIME AND NICHE

8. Moving on to LNG as a ship fuel, how did xx (relevant area for interviewee) get involved in LNG bunkering developments? Can you tell me a bit about this process?
9. Could you describe the main conditions that supported the development of LNG as a ship fuel in Norway?

Probe: How did this change over time?

10. Who were the main actors that supported the development of LNG as a ship fuel in Norway?

Probe: Did the partners have 'personal relations' or 'acquaintances' across the project team?
EMPOWERING/NURTURING—NICHE

11. What expectations did the xx (relevant area of interest) and your partners have from using LNG as a ship fuel?

Probe: Did these expectations differ between different actors and if so, how?

12. Can you think of any groups or organisations that have been particularly vocal in supporting the use of LNG as a ship fuel?

Probe: Could you give specific examples?
END

13. And finally, as we approach the end of the interview, could you suggest any other relevant people that could be relevant to interview with respect to LNG developments as a ship fuel?

5. **'Thank you' statement: Finalize the interview with the following statement:**

'Thank you very much for your time, those are all the questions of this interview. If there is any other information you would like to share with me that has not been covered in the preceding questions, you can share it now'.

PAUSE

'If you have any more questions concerning the interview process and write-up you re welcomed to ask me now or contact me later'.

PAUSE

'This concludes our interview; thank you for your contribution'.

6. **Probes to use during interview to extract more information:**

Use a combination of different probing techniques depending on specific circumstances:

(i) Silent Interviewer—remains silent and allows the participant to think aloud.
(ii) Verbal agreement—expresses interest in the participant's views with the use of phrases, such as '*uh-huh*', '*yes, okay*', and '*Tell me more*'

Appendix C

Table A2. Outline of interviewee response rate by group.

Group	Invited	Interviewed	Response Rate
Bunkering providers	15	8	53%
Policymakers/authorities	20	9	45%
Engine manufacturers	10	2	20%
Shipowners/operators	30	10	33%
Classification societies	5	2	40%
NGO/IGO/other	20	10	50%
Total	100	41	41%

Appendix D

Table A3. Outline of interviewee experiences.

Type of Experience	Number of Interviewees [1]	% Out of Total
Senior corporate executive	21	51%
IMO delegate	9	22%
LNG R&D expert	7	17%
Senior policymaking executive	16	39%
15+ years relevant experience	14	34%
10+ years relevant experience	16	39%
5+ years relevant experience	11	27%

[1] Totals are greater than 41, because some interviewees were involved in multiple relevant roles over the course of their careers. For example, IMO delegates might have also been national policymakers.

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