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Retrofitting towards a greener marine shipping future: Reassembling ship fuels and liquefied natural gas in Norway

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ABSTRACT

The reduction of greenhouse gas emissions has entered regulatory agendas in shipping. In Norway, a debate has been ongoing for over a decade about whether liquefied natural gas (LNG) ship fuel enables or impedes the transition to a greener future for shipping. This paper explores the assembling of ship fuel before and after the introduction of a controversial carbon tax on LNG. It reconstructs how changes in the regulatory apparatus prompted the reworking of natural gas into a ship fuel, yet later slowed down the development of LNG in a strategy to promote alternative zero-emission fuels such as hydrogen. Following ship fuel as socio-materiality in motion, we find that fossil fuels are reworked into new modes of application as part of transition policies. Natural gas continues to be enacted as an "enabler of transition" in the context of shipping, given that current government policies work to support the production of hydrogen from natural gas and carbon capture and storage (CCS). New modes of accounting for emissions reassemble existing fossil fuel materiality by means of CCS and fossil-based zero-emission fuels. We examine retrofit as a particular kind of reassembling and as a prism for studying the politics of fuel and the relation between transitions and existing infrastructures.

1. Introduction

Ships are among the largest machines on the planet and transport most of the traded goods [1]. With global supply chains, the outsourcing of production and the logistics of just-in-time delivery, the amount of goods being shipped across oceans has been increasing over the past decades, and projections for expected increase in seaborn trade by 2050 range from 25 to 180 percent [2]. The towering vessels transporting these goods need vast amounts of energy, and with a few exceptions, they rely on fossil fuel infrastructures, and the land-based regulations that govern these. This includes the most widely used fuel in sea transport, heavy fuel oil (HFO), and another common fuel, marine gasoil (MGO), a distillate oil that fuels most Norwegian ships operating in Norwegian seas. Among the alternatives proposed to oil-based fuels is the use of liquefied natural gas (LNG), which by most accounts cause less emissions compared to traditional fuel [3,4]. Globally, investment in LNG bunkering (refuelling) is increasing [5], but the Norwegian market is declining even though the country was among the frontrunners in developing LNG ship fuel. In this paper, we examine the rise and fall of LNG ship fuel in policy agendas over the past decade in the context of Norway, whose largest export industries are shipping and petroleum, and which is the third largest exporter of natural gas in the world [6,7].

Combustion processes of ship fuel provide the energy for the engine that activates propelling screws and generates thrust. As the fuel molecules are broken down in combustion, they result in emissions and release carbon dioxide (CO_2), nitrogen oxides (NO_x), sulphur oxides (SO_x), particulate matter (PM) and other components [8,9]. While air pollution from shipping has been on the agenda of regulation for decades, both in Norway and in the International Maritime Organization (IMO)[1] [8], the reduction of greenhouse gas emissions slowly entered national and international regulatory agendas during the years leading up to and following the Paris agreement in 2015. Several fuels have been suggested to reduce emissions from ships and make shipping "greener", but shipping is "slow to change" [11] since ships have an expected lifetime of 25–30 years [12] and require substantial physical infrastructures along the coast in order to operate. The Norwegian government in their action plan for green shipping claims that "Norway is playing a leading role in the green transition in international shipping" [13], and the shipping industry frequently turns international attention to the fact that Norway's fleet includes a large proportion of advanced

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[1] IMO is a United Nations specialised agency with the responsibility for the safety and security of shipping and the prevention of marine pollution by ships [10].

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and specialised vessels, including the world's first battery-electric ferry [14,15].

This paper focuses on coastal shipping, more specifically vessels operating on relatively long distances in domestic waters. While battery-electric solutions dominate the segment on short distances, the most commonly discussed alternative fuels to reduce emissions from longer distances in coastal shipping include battery hybrids (meaning vessels that combine batteries and other alternative fuels), hydrogen and ammonia, biodiesel and biogas, and LNG [13,16]. Taking our point of departure in the debate over LNG ship fuel and ending up in the current debate over blue hydrogen, we conduct a close examination of recent regulatory efforts to reduce emissions from ship fuel. While some historians have claimed that the Norwegian shipping industry has been shielded from government interference and profited from a high degree of autonomy [17], this paper demonstrates how ships operating in domestic waters must comply with regulations of the land-based infrastructures that they rely on. Natural gas entered policy agendas as a potential ship fuel around 1996, and in the following years the Norwegian government made several regulatory interventions and investments to accommodate LNG ship fuel, but by 2018 most of these incentives had been removed, and a carbon tax exemption on LNG ship fuel was withdrawn.

In the Fifth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC) [18], natural gas is referred to as both a potential "bridge technology" and a "transition fuel" in combination with variable renewable sources. However, the same IPCC report also states that large portions of the existing fossil fuel reserves must stay in the ground if climate policy targets are to be achieved, which has become a core argument of climate activists and NGOs, giving rise to the "carbon budget" as an alternative mode of calculation [19,20]. This duality, where the object fossil fuels is framed as both an enabler of transition and the very thing we are transitioning away from, can also be found in transition research:[2] Goodman and Marshall [23] draw a line between initiating energy decarbonisation and advancing the fossil fuel sector, and Loorbach et al. [11] write that even though a sustainable society requires changes that go beyond improvement of the existing, present policies often fail to address the underlying structure of problems. In this understanding, infrastructures tend to present a barrier to fast and fundamental change [11]. Other researchers in transition studies hold that established infrastructures do not necessarily impede what they call "radical innovation", and argue that novel technologies may be used in existing infrastructures and structural configurations of a sector [16:2]. This case study examines how this very tension plays out in transition attempts towards greener shipping. Taking a socio-material approach, we show how natural gas has been and still is enacted as a force in transition efforts in Norwegian coastal shipping. Hence this paper examines the negotiations over pathways to a greener future and follows fossil fuels through policies towards green transitions in marine shipping.

2. Studying transition efforts as retrofits of existing infrastructures

To examine the forces that shape, promote or impede the politics of ship fuel in Norway, we draw on scholarship inspired by actor-network-theory (ANT) and studies of infrastructure, as they have emerged in the social sciences and humanities [24–27]. Similarly to transition research, which studies changes in "infrasystems" [11], recent work in infrastructure studies has developed a broader conceptualisation of infrastructure that analyses both technical infrastructures and regulatory infrastructures together [26]. Hence, we examine how regulations, materials and technologies come to act on and shape or foreclose possible futures. One of the core propositions of ANT is that both human and non-human actors, such as fuel, bunkering infrastructure and regulatory documents, participate in shaping the world [28,29]. Murphy et al. [30] have emphasised the importance of including materiality and non-human perspectives in the energy space, and ANT enables such inclusion as we investigate transition efforts as socio-material arrangements in which ship fuels are "reassembled" [31] in a continuous process of assembling associations between elements. Taking on an ANT approach we follow the ongoing socio-material assembling of ship fuels over the past two decades in Norway, where currently hydrogen is on the rise and LNG on decline.

This paper contributes to the growing field of research on shipping in the context of energy and climate policy, many of which focus on Norway [15,16,32,33]. Transition research on infrastructures traditionally seek to identify and understand the patterns of fundamental change, how major transformations that lead to long-term change unfold, what drives these transformations, and how actors participate in these processes [11,34]. For example, in a recent study of sustainability transition within the maritime sector in Norway, Bach et al. [16] discuss whether the interchangeability between fossil fuels and biofuels could provide an opportunity of a rapid transition to fossil free energy sources. As an addition to these approaches, this paper shifts the focus to how transitions are practiced and negotiated: Amundsen and Hermansen [35] establish that few empirical studies investigate how transformations actually manifest in practices. Contributing to STS-based approaches to transitions and socio-technical matters [36], we go beyond parts of the long-standing socio-technical systems tradition [21,22]. We examine how transition work is enacted in regulatory work to enable greener shipping, by building on Howes et al.'s [26] conceptualization of "paradoxical infrastructures". Our approach takes infrastructure as a capacious socio-material concept to analyse debates over how to fuel ships. Building on this conceptual toolbox of ANT and infrastructure studies, we follow ship fuels as materiality in motion while also attending to the endurance [37] of infrastructures.

Barry [37,38] encourages us to attend to the diverse ways in which infrastructures shift and mutate over time, since infrastructures need additions, maintenance and repair to avoid breaking down. Hence, the endurance of infrastructures should be studied as an ongoing process of socio-material transformation [37:94]. The analysis foregrounds the concept of retrofit, a term used by actors in infrastructure building and in shipping. We use the term retrofit in line with the conceptualization by Howe et al. [26] in order to open up our case of green shipping for the study of socio-material reconfigurations and temporalities in ship fuels [37,39]. They argue that "In order to operate over long periods of time, old infrastructural designs must be constantly retrofitted to meet new contingencies" [26:553], and define retrofit as an attempt to bridge timelines. In this paper we examine retrofit as a particular kind of reassembling, and as a prism for studying the politics of fuel and the relation between transitions and existing infrastructures.

3. Methodological approach and empirical materials

This case study relies on qualitative data, and includes interviews, participant observation and document analysis. Our work is based in an understanding that all methods enact realities, meaning that they performatively shape the social [40,41]. Using an inductive and exploratory approach [42] aiming to access green shipping in depth, we initiated our studies in the context of a public–private partnership. The paper draws on 14 interviews with 14 representatives in this partnership from different segments of the Norwegian maritime sector, including ship owners, business actors, service suppliers, interest organisations and ministry representatives working on topics related to developing alternative ship fuels. All interviews were semi-structured, they were conducted face to face and lasted about one hour. The interview guide included questions that focused on the dynamics of the partnership, and

[2] In much of the social science literature on sustainability transition, "transition" is a term used to address dynamical processes, including governance of and normative goals in developing socio-technical systems [21,22].

more importantly questions that became the foundation of this case study, focusing on the actors' understanding of "green transition", "green shipping" and "green fuel". Tension over the greenness of LNG ship fuel came up from the outset of the empirical work as an interesting case to pursue in an analysis of the stakes and practices around ship fuel over the past 20 years. In addition to interviews, materials consist of observations at conferences and seven partner meetings in the partnership between 2016 and 2018, the period a carbon tax was introduced on LNG. The partnership served as a point of departure for further inquiries into the controversy on LNG ship fuel.

To access policy agendas and the efforts to regulate LNG ship fuel, we analysed government documents including reports from Norwegian Parliament hearings, motions and white papers, following LNG as it was promoted by incentives and later regulated by taxes. Documents that shed light on the political debates and decision-making processes that led to the development of LNG ship fuel and the following introduction of the carbon tax were selected. Additionally, this study is based on strategies and action plans that highlight policy agendas in the field of ship fuel, as well as media publications and reports commissioned or written by business actors, researchers and organisations. Analysing these documents, we focused on the framings and reassembling of natural gas as ship fuel, following natural gas in debates over LNG ship fuel into newer debates over blue hydrogen.

We narrowed down the study to a focus on regulation and two of the alternative fuels currently considered for shipping. Based on the materials that inform this case study, we identify two regulatory changes that became key to the reassembling of ship fuel: (1) how LNG ship fuel emerged as an alternative fuel and subsequently a ship fuel, and (2) the subsequent regulatory changes that subjected LNG ship fuel to a carbon tax, motivated by the ambition to stimulate the use of other alternative zero-emission fuels including hydrogen. Our attention to the materiality of LNG ship fuel motivated an examination of LNG as a mixture of hydrocarbon gases and the physical infrastructures that enable the production and distribution of LNG ship fuel. The analytical unit that we followed through its socio-material transformations – natural gas in the context of ship fuel – was shaped inductively during our investigations.

4. Existing natural gas infrastructure and greener shipping

Liquefaction has made it possible for natural gas to be shipped around the world by sea as a commodity for over half a century. When brought to land in ships with cryogenic tanks, LNG goes through a regasification process where it is converted back to natural gas and used for purposes such as industrial processes and heating. Mobilising LNG and obtaining liquefaction require advanced cooling technology, called the cryotechnological process, that transforms the materiality of gas into a liquid and reduces the volume of natural gas more than 600 times, making it easier and safer to store and transport LNG independently of pipelines [43]. While the vast majority of Norway's natural gas is supplied through pipelines, a small amount of the gas is exported as LNG. The LNG is primarily produced on a large scale in a facility run by the state-owned energy company Equinor, making Norway the only LNG-producing country in Europe [7]. The Equinor facility receives and processes natural gas from the Barents Sea, and before it is converted to LNG, some of the CO_2 fraction contained in the natural gas is returned to the field and injected in a separate formation under the reservoirs. Describing this as one of the few carbon capture and storage (CCS) projects in Europe [44], the Norwegian petroleum industry works to prevent the "excess" CO_2 contained in the extracted gas from being released into the atmosphere, but CO_2 is still released once the exported gas is combusted. Major investments have been made in CCS technology [45].

Norway was central to the development of LNG as an alternative fuel *for* ships, rather than as an energy commodity to be transported by ships elsewhere for export. As early as the 1960s, boil-off gas (natural gas) of LNG carrier ships was occasionally used as ship fuel [46], but it took another four decades until a ship was fuelled solely by LNG. Building on its existing infrastructure and competence, Statoil, now Equinor, launched the country's first LNG project Tjeldbergodden in western Norway, which laid the foundation for the ferry MF Glutra. The ferry set sail in 2001 and was "enchanted"[3] with much hope and expectation as the world's first ship solely fuelled by LNG [47]. Hence, the access to Norwegian-produced LNG and Norway's engagement in the LNG market enabled the development of LNG-fuelled shipping in the late 1990s [48]. This expanded into an LNG ship fuel infrastructure, including the equipment and facilities for transport, such as small-scale LNG carriers and gas tanker trucks, storage including LNG terminals during and following transport, and bunkering of LNG ship fuel [49]. Today, Norway's bunkering infrastructure, comprising about ten facilities where ships can receive LNG ship fuel, makes it quite developed compared with other countries [13,50]. In the first two decades of the 21st century, almost 70 Norwegian LNG-fuelled ships were built [51], but these still make up a small share of the ships operating on domestic seas.

The development of an LNG ship fuel infrastructure did not occur in a vacuum; several concerns related to different evolving "political situations" [37:103] motivated its development. Originally, LNG ship fuel was backed by decision makers who were increasingly addressing the concern about air pollution [48]. Most research concludes that compared with traditional fuels, LNG ship fuel nearly eliminates SO_x emissions and PM and reduces 80–90 percent of NO_x emissions [3,4,52]. In 1996, the Norwegian Parliament [53] suggested that the government should consider supporting pilot projects that would develop ferries fuelled by LNG as part of a national strategy for reducing Norwegian NO_x emissions, yet at that point in time, the concern for greenhouse gas emissions was not mentioned. Policy makers introduced a tax on NO_x emissions in domestic shipping in 2007, as well as helped in the establishment of the NO_x fund, which still financially supports NO_x-reducing projects and has been instrumental in setting the stage for the use of LNG ship fuel [48,54]. In a retrofit, natural gas had become key to fuelling Norwegian ships in efforts to make coastal shipping greener.

5. A disputed carbon tax exemption: can LNG enable transitions?

In the 2000s, the concern about greenhouse gas emissions from ships increased and developed as a political situation with its own trajectory, which brought along a new role for LNG ship fuel to play. In 2008, the Norwegian Parliament agreed on aiming for "carbon neutrality" by 2050 [55], and in its white paper leading to this agreement, the government proposed "building up infrastructure for the distribution of natural gas, among other things to facilitate the introduction of ferries fuelled by natural gas"[56].[4] Particular calculations accompanied this new framing, as the white paper argued that the environmental benefits would be "considerable", given that LNG ship fuel nearly eliminates air pollutants and reduces greenhouse gas emissions by "20–25 percent" [57]. Hence, in this new framing of LNG ship fuel, natural gas contributed considerably to climate policies in the attempt to make LNG ship fuel an "enabler of transition". Policy makers then made use of the carbon tax to promote LNG ship fuel, a tax known as "the main instrument" in Norwegian climate policy [58]. The carbon tax was first introduced in 1991 [59], and during its existence, carbon tax exemptions, which some economists would call "incentives", have been given to sectors and products to ensure their ability to compete in the market. Natural gas

[3] We use this term in the sense of "enchantment of infrastructure" as described by Harvey and Knox [25].

[4] Translated from Norwegian

used as ship fuel even continued to be exempt from the carbon tax when natural gas was deprived of its previous exemptions in 2010 [60]. One political party opposed the decision to exempt LNG ship fuel in 2010, pointing to the "polluter pays principle" [60], hence advocating a calculative approach in which greenhouse gases are accounted for. This argument was dismissed, and the carbon tax exemption was maintained, in ANT terms, as a device of "interessement" [61] created by the government to preserve favourable regulatory terms for the use of LNG ship fuel.

The framing of LNG ship fuel as key to meeting climate targets was challenged when LNG ship fuel was subjected to the carbon tax. When the Norwegian government first proposed removing the carbon tax exemption for LNG ship fuel in domestic shipping in 2017, heated debates followed, and promoters of LNG in the shipping industry wrote opinion pieces, lobbied and attended hearings in order to stop the tax from becoming a reality. An opposition party argued that the carbon tax would dismiss "something which could have been an opportunity to build future-oriented ships in a transitional phase towards a low-carbon society" [62].[5] In an attempt to get the carbon tax decision reversed, a 2018 report commissioned by several actors in the shipping industry presented calculations supporting the argument that Norway must replace a substantial share of its fleet with LNG-fuelled ships to meet its climate policy targets. The report argued that LNG ship fuel offered low-emission fuel for ships operating on relatively long distances along the Norwegian coast, where battery-electric technology fell short, biofuels were hard to come by and expensive, and hydrogen and ammonia were still being developed as ship fuels [63]. These statements advocate natural gas as important energy source in transitions. Furthermore, framings of natural gas as an enabler of transition in shipping went beyond calculation and became increasingly complex as they addressed physical infrastructures as enablers of transitions. For example, advocators described LNG ship fuel as a "a bridge-builder in order to phase in biogas as a ship fuel" [64],[6] given that LNG-fuelled ships may be retrofitted to accommodate biogas, which is combinable and replaceable with LNG, also making it possible for the bunkering infrastructure for LNG ship fuel to accommodate biogas [16,63,65]. However, policy makers in favour of a carbon tax on LNG ship fuel put forward alternative calculations and framings in which the LNG ship fuel infrastructure impede, rather than enable transitions.

6. The end of natural gas in Norwegian shipping? Carbon tax on LNG ship fuel

As several stakeholders in the Norwegian shipping industry and some political parties had feared, a carbon tax on LNG ship fuel was introduced in 2018 (See Table 1). LNG-fuelled vessels operating between ports in domestic waters were subjected to the same taxation as ships running on oil-based fuels and had become a target for Norwegian climate policy instruments. Ship owners were now facing a price of LNG ship fuel 25 percent higher than regular fuel [64], and many lost their LNG investments when the LNG market did not take off in the way that had been expected [32]. Out of the around 170 LNG-fuelled vessels currently planned for 2022 globally, only one is Norwegian [51]. When asked to explain the introduction of a carbon tax on LNG ship fuel, the government argued that "The carbon tax strengthens the incentives for developing low- and zero-emission solutions for domestic shipping, such as hydrogen-fuelled vessels, battery- fuelled vessels and battery hybrids"[7] [66]. Here, the government arguably framed an expansion of the LNG ship fuel infrastructure as something that could happen at the expense of other alternative fuels that enable transitions.

Table 1
LNG ship fuel development in Norway.

Year	Development	Institution(s) involved	Relevance
1996	The Norwegian Parliament suggested supporting pilot projects that would develop ferries fuelled by LNG.	The Norwegian Parliament	Policy makers signalled an interest in LNG ship fuel.
1998	First LNG project on Tjeldbergodden.	Statoil (now Equinor)	The energy company was the first to develop LNG in Norway.
2001	The ferry MF Glutra set sail in 2001 after a development contract was initiated by the Norwegian Public Roads Administration [16].	Norwegian Public Roads Administration and Møre and Romsdal County Boats (now Fjord 1)	This was the world's first ship fuelled solely by LNG.
2005	The Gothenburg Protocol, an international agreement to reduce substances such as NO_x and SO_2 entered into force.	Norway and several other countries	International agreements including the Gothenburg Protocol led to an increased focus on LNG ship fuel.
2005	MARPOL Annex VI was adopted in 1997 and entered into force in 2005.	IMO	International regulations led to an increased focus on LNG ship fuel.
2007	NO_x tax on fuels in domestic shipping was introduced as a means to comply with the Gothenburg protocol [67].	Norwegian government	National regulations led to an increased focus on LNG ship fuel.
2008	The NO_x fund was established.	Norwegian companies	The NO_x fund has contributed to the use of LNG ship fuel and expansion of an LNG ship fuel infrastructure.
2008	The Norwegian Parliament agreed on aiming for "carbon neutrality" by 2050.	Norwegian Parliament and Norwegian government	To achieve carbon neutrality, the government proposed to build up infrastructure to facilitate ferries fuelled by natural gas.
2010	Carbon tax exemption on natural gas was removed.	Norwegian government	LNG ship fuel was still exempt from the carbon tax.
2018	Carbon tax exemption on natural gas as ship fuel was removed.	Norwegian government	LNG ship fuel was no longer exempt from the carbon tax.

In the aftermath of the carbon tax introduction, government documents have mobilised new calculations that give rise to new orderings. In its action plan for green shipping from 2019, the Norwegian government stated that the reductions in greenhouse gas emissions by most of the LNG ships operating in Norwegian waters are "on average 12 percent", which is low compared to previous estimates published by the government, and furthermore, the action plan refer to the emission reductions from LNG ship fuel as "minor".[8] The action plan also mentions concerns about the methane leakage and the problem of unburned methane when an LNG-fuelled ship emits exhaust [13]. Arguably, these numbers and evaluations question whether LNG ship fuel helps meeting

[5] Translated from Norwegian
[6] Translated from Norwegian
[7] Translated from Norwegian
[8] Translated from Norwegian

climate targets. The issue of LNG ship fuel can be understood as a matter of different and at times contradictory translations and ways of assembling. Currently, regulations enact transitions in which LNG ship fuel belongs to the strategies of the past, and LNG ship fuel may have lost some its relevance as a "green fuel" in Norwegian coastal shipping.

As we have attended closely to the materiality of LNG, both the natural gas of which it is composed and the natural gas infrastructure that enables its production and existence, we have rendered visible the dynamic relation between regulation, infrastructure, and retrofit: the introduction of the carbon tax may have led to a decline in newbuilt LNG-fuelled vessels in Norwegian seas, but something remains. The natural gas infrastructure endures, and is currently enacted as an enabler of transition in shipping, given that it can be used in the production of blue hydrogen. Hence, we continue to follow natural gas and the ongoing reassembling of ship fuels, and in the next section we describe this new potential retrofit of fossil fuels.

7. As LNG is in decline, hydrogen is on the rise in a retrofit of fossil fuels

The carbon tax on LNG ship fuel was never a rejection of natural gas as an enabler of transition in shipping. As shown, the tax on LNG ship fuel was a strategy to provide incentives for the development of other fuels, and in the years both leading up to and following the carbon tax introduction, one of the fuels promoted by the government, was hydrogen. Hydrogen powers cars, trucks and trains, but it is primarily used as chemical feedstock, such as in ammonia production [68], and has never been used to fuel large ships. In 2016, the Norwegian Parliament asked the government to consider supporting pilot projects in order to explore hydrogen-fuelled ferries [69]; four years later, the government launched its first hydrogen strategy [70]. Even though hydrogen-powered ships pose substantial challenges including potentially high costs and limited accessibility and bunkering infrastructure, not to mention that hydrogen is highly explosive [70], the enthusiasm from Norwegian policy makers prevails. Hydrogen production facilities are in the planning phase, fuel cell factories are under construction, and pilot projects are testing hydrogen in combustion engines [71,72]. In the beginning of 2021 a Norwegian ferry with fuel cells installed set sail, which the government and industry believe may be the world's first ferry fuelled by hydrogen once liquid hydrogen has been delivered from Germany [49,73]. In visions of hydrogen produced for maritime use in Norway, one out of the two most-discussed options depends on natural gas.[9]

The hydrogen expected to fuel ships has been attributed many different colours. Hydrogen is an energy carrier and not an energy source, which means that it needs to be produced from other sources of energy [68]. Currently, hydrogen is mainly produced through a process of "reforming" fossil fuels, which is the conversion of hydrocarbons, and it has been referred to as "grey hydrogen" when produced from natural gas [68,74]. So far only small proportions of hydrogen are currently produced by means of electricity generated by renewable energy sources and using water electrolysis, and it is often referred to as "green hydrogen" [75]. Hydrogen has also been labelled with another colour – "blue" – which refers to a way of potentially producing hydrogen, combining natural gas and CCS, where proponents imagine that most of the CO_2 that is emitted in the production of hydrogen from natural gas, with the exception of a few percent, may be captured and stored.[10]

According to Damman et al. [78], there are divides and tensions over green and blue hydrogen among Norwegian stakeholders. While most of the current hydrogen production initiatives in Norway explore green hydrogen [78], at the facilities at Tjeldbergodden, which were central to the development of LNG ship fuel, companies are partnering with Equinor to "kick-start blue hydrogen production" [78,79]. When the Norwegian prime minister launched a government-initiated full-scale CCS project in 2020, she expressed that the project could lay the foundation for the use of blue hydrogen in vehicles, ships and industrial processes [80]. The minister of petroleum and energy called it "the biggest climate project in Norwegian industry in our time" [81].[11] In these visions of blue hydrogen, the very materiality of natural gas is reworked: instead of departing from fossil fuels by leaving them in the ground, blue hydrogen is enacted in flexible modes of accounting for carbon which count on capturing and returning most of the emissions to the ground in the production process. In the Norwegian government's hydrogen strategy, blue hydrogen is framed as relevant in the transition to a "carbon neutral" society, and the government reports that blue hydrogen will presumably be less costly than producing green hydrogen [70].

In 2018, the carbon tax on LNG ship fuel was accompanied by the following statement by the Norwegian government: "LNG is a fossil fuel that contributes to CO_2 emissions" [66].[12] However, neither characteristic proved to be reason enough for the government to reconsider energy agendas and move away from fossil fuels. In the government's hydrogen strategy, calculations round down the tonnes emitted to "zero" by establishing that blue hydrogen is a zero-emission fuel as long as it reduces emissions by at least 95 percent [70]. Until present, natural gas still plays a role in powering ships and policy agendas, and visions for green transitions are enacted not as a choice between fossil fuels and fossil free fuels, but as a multitude of possible choices in which fossil fuels potentially has a role to play. As Van de Graaf et al. [68:4] state, blue hydrogen supports continued extraction, processing and transport of natural gas, as well as the CCS industry, and therefore offers a "lifeline to petrostates" into the green transition. In current strategy documents, blue hydrogen is being stabilized as a new kind of pathway in a sociomaterial reshuffling of natural gas. As the carbon tax has arranged for the development of LNG ship fuel and later alternative fuels including blue hydrogen, it builds "alternative temporalities to functioning systems" [39], potentially prolonging the existence of the natural gas infrastructure, in moves that we have identified as retrofits.

Globally, LNG is widely considered a potential transition fuel for decarbonizing shipping, though this is heavily debated [82]. LNG use in shipping has increased fivefold since 2016, and is still increasing primarily because of investments made in China, followed by Europe [5]. Some studies expect that the global demand for LNG bunkering will grow rapidly towards 2050 [83], while the International Energy Agency (IEA) casts doubt about demand growth beyond 2024 due to "the inability of LNG to meet the IMO's long-term GHG reduction targets" [5]. Here, IEA refers to recent developments in the IMO and an initial Strategy on reduction of greenhouse gas emissions from ships, which was adopted in 2018, stating that the global shipping community aims to reduce its greenhouse gas emissions by 50 per cent compared to 2008 and then phase them out [84]. In the EU, transition efforts mainly focus on green rather than blue hydrogen [79,85], but blue hydrogen is indeed mentioned in international policy agendas. In a 2021 report, the World Bank argues against LNG ship fuel as transition fuel, but states that "it is quite possible that natural gas could play an important role in shipping's decarbonization as a feedstock for the production of zero-carbon bunker fuels such as blue hydrogen" [86]. Furthermore, transition researchers studying global energy development report that a full-fledged "clean hydrogen" infrastructure is unlikely to happen without blue hydrogen, "given the current scale and cost advantage of hydrogen production

[9] To limit the scope of this study, we do not discuss ammonia, even though there are several ongoing Norwegian projects working to enable ammonia-fuelled ships. However, since ammonia is a hydrogen-based fuel, developments in blue hydrogen can shed light on blue ammonia produced from natural gas.

[10] In some cases, hydrogen is also referred to as "turquoise" and "red" [76,77].

[11] Translated from Norwegian

[12] Translated from Norwegian

from fossil fuels" [68:2]. We believe that this case study in the context of Norway can provide insights that are valuable as efforts are made to reduce emissions from shipping globally.

8. Conclusions

In this paper, we have investigated the reassembling of ship fuels during two regulatory changes in the context of Norway, a country that identifies itself as an "energy nation" [45]. We have followed the processes that mobilised natural gas as ship fuel when the regulatory infrastructure rendered LNG ship fuel exempt from the carbon tax, and the modes in which natural gas was remobilised in new visions of greener ship fuels when this exemption came to a halt. Describing this regulatory intervention and the response to regulation that followed – remobilization – shines light on how policy measures can result in strategic retrofitting of existing infrastructures. Adding to the literature on how infrastructures shape and are shaped by policies and technosocial change [26,37,38] we have described the reassembling of existing infrastructures as contested retrofits, showing how energy infrastructures such as the Norwegian natural gas infrastructures strive to endure, but require maintenance and additions to do so. These analyses have rendered visible and characterised tensions and dilemmas in the ongoing reassembling of ship fuels in new mixtures. Through multiple processes of retrofitting – material, economic and political – transitions are mediated through simultaneous and heterogeneous assembling practices that can both uphold and challenge natural gas as an enabler of transition in shipping. Even in newly assembled scenarios beyond LNG, the very materiality of natural gas is still present, modified by CCS technologies and revised calculative tools, retrofitted towards zero-emission fuels in efforts to produce blue hydrogen.

Fossil fuels are not renewable, and at one point they will run out. However, current transition efforts in Norwegian coastal shipping enact fossil fuels as forces in transitions, rather than making a clear-cut demarcation between fossil fuels and transitions. Energy production, industries, as well as contemporary institutions and even "democratic machineries" [87], have been engineered around fossil fuels for decades, and as such, fossil fuels have enabled and maintained the current forms of political and economic life in industrialised countries [87]. As Howe et al. [26] have aptly pointed out, retrofitting necessarily builds on past projects and current materials and technologies. Recent transition strategies of green shipping envision versions of change that have so far largely remained bound to the fossil fuel era. As they respond to regulations by adding retrofitted versions of fossil fuel infrastructures, these modifications also present retrofits of the fossil fuel economy in which Norway is deeply embedded. Staying with the materiality of fuel in qualitative social studies of energy transitions may open up for research that conceptualize the socio-material dynamics of transition and retrofit in and beyond the maritime sector.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.erss.2021.102423.

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