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Does time matter? A multi-level assessment of delayed energy transitions and hydrogen pathways in Norway

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ABSTRACT

The Russian invasion of Ukraine has undeniably disrupted the EU's energy system and created a window of opportunity for an acceleration of the low-carbon energy transition in Europe. As the trading bloc's biggest gas supplier, Norway faces the imminent threat of fast-depleting gas reserves and declining value for its exports. Norway is trying to beat the clock by aggressively exploring more petroleum, therefore delaying its energy transition. In anticipation of the future drop in gas prices, Norway is counting on blue hydrogen to valorise its gas resources, before gradually shifting to green hydrogen export. Against this background, this article seeks to understand how changes in the EU's energy landscape have affected the energy export sector and low-carbon hydrogen export developments in Norway from a multi-level perspective. Using the exploratory scenario approach, the article assesses the implications of the different petroleum exploration outcomes on the development of the low-carbon hydrogen export market in Norway. The findings show that despite gas discoveries, there is an urgent need for a phase-out plan for the Norwegian petroleum sector. For low-carbon hydrogen to play an important role in Norway's energy transition, time is of the essence and action needs to be taken during this window of opportunity. An industrial sector and its value chain could take 25 years to transform, which means that actions and policies for a full transformation pathway need to take place in Norway by 2025 to be ready for a climate-neutral Europe in 2050.

1. Introduction

Threatened by Russia's weaponization of gas supplies, the EU plans to drastically reduce its dependence on Russian gas. Some of the gas demand will be replaced by 20.6 million tons of green hydrogen by 2030, of which about half will be imported [1]. A successful low-carbon energy transition in the EU will not only reduce petroleum imports within its borders but will likely inspire other petroleum-dependent importers to follow its lead and further reduce the global demand for natural gas (hereinafter gas). Countries whose economies are highly dependent on petroleum exports need to take the transition seriously or risk ending up with stranded assets [2]. Norway is likely to be the first to be affected since more than half of its 2021 total exports come from petroleum exports to the EU [3]. This risk can be mitigated by leveraging its technological expertise and natural resources to establish a new export industry based on blue and green hydrogen.

Rather than phasing out its petroleum industry now, the Norwegian government seems to be delaying its energy transition by exploring more hydrocarbon and maintaining a high level of activity in the Norwegian Continental Shelf [4]. Following the Russian-Ukraine war, this strategy has been endorsed by the EU, making the possibility highly likely in the coming years [5]. Further exploration comes with high risks of failure because much of the undiscovered gas resources are in the largely unexplored Barents Sea [6]. Furthermore, it takes on average, twelve years to get the gas to stream from discovery [7]. Therefore, there is a risk that the EU may no longer need the gas by the time it comes to stream and that the remaining gas would lose its value.

For low-carbon hydrogen export to be economically feasible, large-scale production is critical to gain economies of scale. Blue hydrogen production requires gas and Carbon Capture and Storage (CCS) technology and is deemed to be more scalable than green hydrogen in the short term. Accordingly, the Norwegian Hydrogen Roadmap expects blue hydrogen to play a domineering role in the low-carbon hydrogen export market until 2050, whereas green hydrogen will only be used in small-scale applications [8]. This suggests that the Norwegian government is counting on blue hydrogen exports to valorise the remaining gas

Abbreviations: CCS, Carbon Capture and Storage technology; EU, European Union; EUR/tCO_2e, Euros per ton Carbon Dioxide equivalent; Km, Kilometre; LNG, Liquid natural gas; NOK, Norwegian kroner.

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reserves and infrastructure, which may otherwise be stranded.

Norway has both ample freshwater resources and a near-100 % green electricity supply to produce green hydrogen competitively at a large scale. Under normal circumstances, Norway has a competitive advantage over the EU as electricity prices are relatively cheaper. By 2030, green hydrogen is expected to be more price-competitive than blue hydrogen due to higher potential technological and electricity price improvements [2,9]. Electricity accounts for 65–80 % of green hydrogen production cost [9] and electricity prices in Southern Norway and the EU, whose power grids are closely connected, are sky-high due to the war. Electricity prices in Northern Norway remain relatively low because of the limited transfer capacity between the Northern and Southern power grids [10]. Therefore, it is cheaper to produce green hydrogen in Northern Norway than in Southern Norway and the EU [11].

Previous research on hydrogen exports in Norway showed that blue and green hydrogen exports can play a key role in its low-carbon energy transition away from a techno-economic perspective [12–15], a socio-technical perspective [16] and a geopolitical perspective [17,18]. These studies were mostly conducted before the energy landscape changes linked to the Russian-Ukraine war, particularly regarding the EU's support for Norway's petroleum exploration. This contradicts its position articulated in the EU Arctic Strategy, where the EU stated their preference to keep fossil fuel in the ground [19]. In earlier studies, the phase-out of petroleum exports was assumed in assessing the potential for hydrogen exports in Norway [16]. Given the intricate relationship between hydrogen and gas, assessing the implications of delaying the phase-out of the petroleum sector on low-carbon hydrogen exports is important.

The article takes as its departure point, a climate-neutral Europe by 2050. The export routes for both blue and green hydrogen are explored and compared between two scenarios: "Business-As-Usual" and "Inevitable Transition". Given the renewed interest in further petroleum exploration, it is important to explore how the above-mentioned outcomes will affect the future developments of blue and green hydrogen exports in Norway. This article seeks to answer the following research questions: *1) How might the broader energy landscape in Europe affect the energy export sector and hydrogen export developments in Norway?* 2) *What might be the implications of the outcomes of further petroleum exploration on hydrogen export developments in Norway?*

The remainder of this article is structured as follows. Section 2 presents the background on hydrogen in Norway, followed by a presentation of the methodology in Section 3. Section 4 presents the findings and analysis, while Section 5 explores the narratives of the above-mentioned scenarios and how they affect the transition pathways for low-carbon hydrogen exports in Norway. Section 6 concludes with a discussion and a summary.

2. Hydrogen export routes from Norway

Hydrogen has been produced for decades in Norway by two key actors, Yara and Equinor [20]. Yara is one of the world's leading ammonia manufacturers today and has been producing hydrogen to manufacture ammonia-based fertilisers [21]. Equinor is the biggest petroleum company in Norway and is majority state-owned. Equinor uses hydrogen to produce methanol. The hydrogen they produce is known as grey hydrogen, which is produced by steam reforming of gas without CCS. As the production and consumption occur in the same site, Norway has no infrastructure for the transport and distribution of hydrogen. Despite two earlier major interests for hydrogen for decarbonising the transport sector, the current interest in hydrogen is likely to stay due to the falling costs of renewable energy technologies and hydrogen's potential to decarbonise hard-to-abate sectors like the industry, building and power generation sectors [22]. Low-carbon hydrogen is expected to play a key role in the EU's climate-neutrality goal by 2050, but meeting the demand depends partly on imported hydrogen from other countries, as outlined in the RePowerEU plan [1].

The EU is Norway's biggest gas import market and its member states are prohibited to enter long-term gas contracts with non-EU countries that extend beyond 2049 under the Hydrogen and Decarbonised Gas Package of the European Green Deal [23]. This means the future demand for Norway's gas will likely fall significantly by 2049. Further, without long-term contracts beyond 2049, the profitability of new gas production projects may be put in question and fewer funding opportunities may be available for their launch [24]. However, the risks of stranded gas assets could be mitigated by transforming the gas export business to blue hydrogen export, in line with the RePowerEU plan.

To produce large volumes of low-carbon hydrogen (such as 1.5 million tons annually), centralised production is favoured due to the economies of scale. Regardless of the type of hydrogen, a significant amount of electricity is needed for production. Electricity is needed, not only for producing blue hydrogen through gas reforming, but also for capturing, compressing, storing, and transporting carbon from the site of production to the geological site for carbon storage. Further, the hydrogen may need to be purified to enhance its purity from 95 % to 99.95 % or 100 %, the standard purity level for hydrogen applications in industry or fuel cells respectively [25]. In comparison, green hydrogen production only requires electricity for splitting hydrogen from water with an alkaline electrolyser, a relatively mature technology that is considered most well-suited for large-scale centralised production [26]. A cleaning process is not needed as the hydrogen purity is at 100 % [25].

This paper explores the current three most sought-after export routes by Norwegian actors. *Route 1* (Fig. 1) concerns blue hydrogen exports by leveraging on existing gas infrastructure to transport gas from Norway to the recipient country in the EU and producing blue hydrogen near the receiving end of the gas pipelines. Unlike *Route 1*, hydrogen production takes place in Norway in *routes 2 and 3*. *Route 1* favours Equinor, the Norwegian majority-state-owned petroleum incumbent. Equinor is notorious for its excessive influence on the government to fund its projects without much governmental control despite high-cost overruns like the Mongstad CCS demonstration project [27]. Equinor enjoys strong state support for further petroleum exploration, particularly from the two major parties, the Labour Party and the Conservative Party [28]. Equinor is the main actor pursuing hydrogen exports via *Route 1* as it complements the current business portfolio. Despite the nascent technological state of CCS for industrial applications (including blue hydrogen production) and uncertainty in the cost estimates for transporting the captured carbon emissions from the EU to Norway and storing them in the latter's geological sites (as shown by the leftmost red arrow in Fig. 1), *Route 1* is arguably the most cost-effective hydrogen export route among the three because it leverages on existing infrastructure and eliminates the need for hydrogen-dedicated pipelines. However, the infrastructure for carbon transport from the EU to Norway does not exist today. Norway and Germany announced in January 2023 that they will conduct a feasibility study for carbon transport via pipelines from Germany to Norway [29].

Routes 2 and *3* explore the export of locally-produced blue hydrogen and green hydrogen respectively, from Norway to the EU. Hydrogen can be either through hydrogen pipelines (*Route 2a* or *Route 3a*) or by ammonia tankers (*Route 2b* or *Route 3b*). IRENA reports that hydrogen transport via pipelines can be cost-effective for distances of up to 8000 km [2]. The Barents Sea has currently a 160-km long pipeline connecting the Snøhvit field to mainland Norway [30]. The rest of the roughly 9000 km of high-pressure subsea pipelines are in the South, used for transporting gas to Europe [31]. If the pipeline material is compatible with hydrogen, the pipelines could be repurposed at a lower cost by 65–94 % than building new hydrogen pipelines [2]. However, repurposing existing gas pipelines entails the complex coordination of decreasing gas demand and increasing hydrogen demand concurrently [2]. E*xpert A* shared that the challenge of retrofitting existing gas pipelines to hydrogen pipelines is that it has never been done before, unlike building hydrogen gas pipelines. Under the European Hydrogen

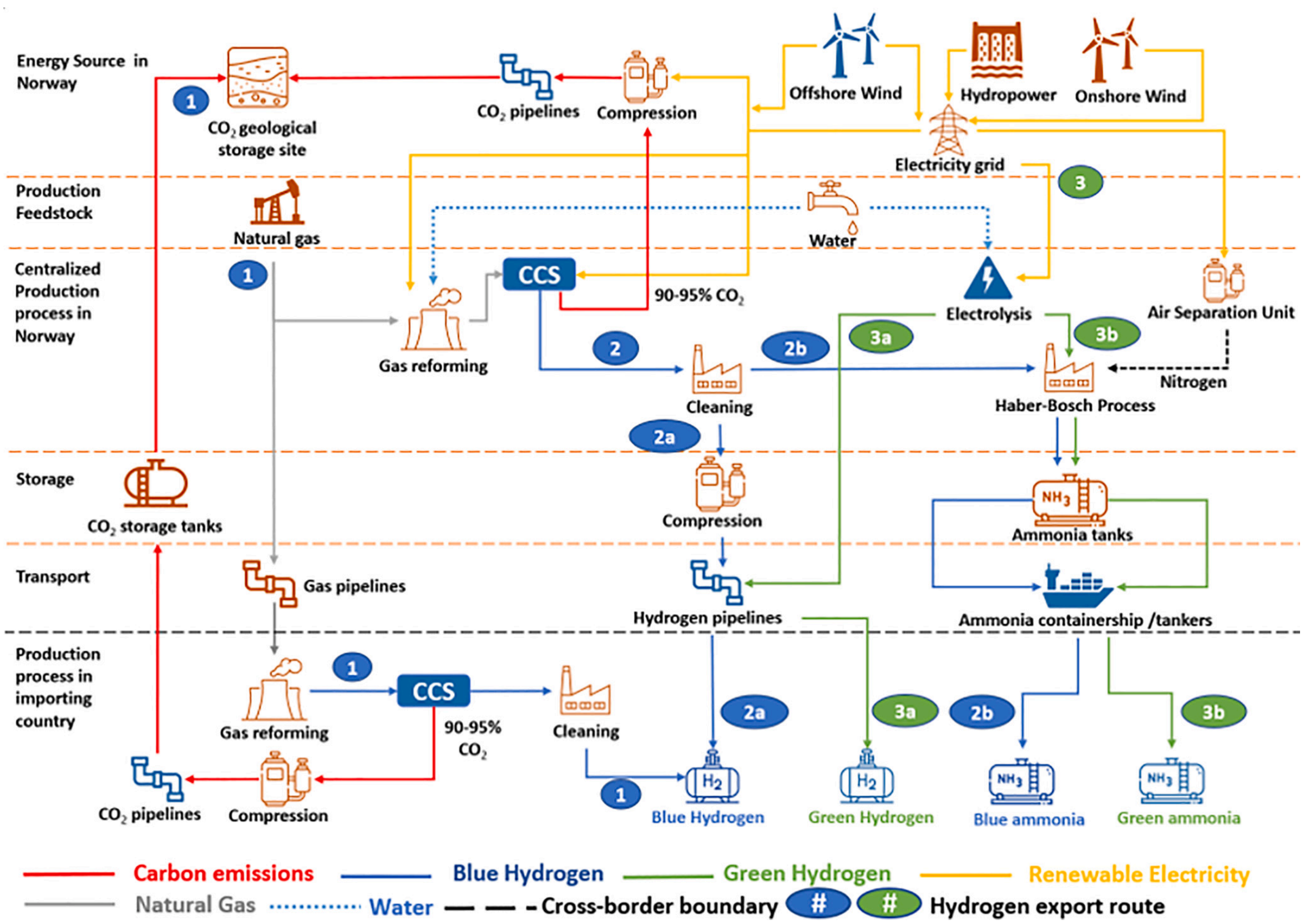

Fig. 1. A simplified and non-exhaustive diagram of hydrogen export pathways from Norway to Europe.[1]
[1]Clipart source: flaticon.com

Backbone initiative to establish hydrogen supply corridors in Europe by 2030, the Norwegian gas transport system operator, Gassco, plans to repurpose existing pipelines to export hydrogen and build a new hydrogen pipeline from Norway to the Netherlands in 2040 [31]. In a joint effort with Germany, Norway is also investigating the feasibility of building a new hydrogen pipeline connecting both countries for blue hydrogen export [29]. These pipelines are likely to be situated near existing gas pipelines in Southern Norway because of the shorter distances to Europe. Hence, *routes 2a* and *3a* could be viable for the blue and green hydrogen exporters in Southern Norway respectively. It is worth noting that Equinor co-owns several existing gas pipelines connecting Norway to the EU [32], making it well-positioned to export via *route 2a*.

Due to the lack of gas infrastructure and long distances from Europe, blue and green hydrogen exporters in Northern Norway are more likely to pursue routes *2b* and *3b* respectively. Ammonia is a hydrogen carrier and when liquified, it holds significantly more hydrogen in a given space than hydrogen in its liquid or compressed form [22]. Ammonia is produced by combining nitrogen, which is extracted from the air, with hydrogen through the Haber-Bosch process. *Routes 2b* and *3b* are widely considered the most promising way for kickstarting the hydrogen export market from Norway to the EU as they can tap into the existing ammonia infrastructure and network to establish the hydrogen economy more rapidly [33]. Furthermore, ammonia can be used to fuel ships running on combustion engines without major modifications. The first ammonia-fuelled cargo ship was delivered in February 2022 [34].

3. Conceptual framework and methodology

This article is a qualitative study that combines the use of the multi-level perspective framework and the exploratory scenario framework. The multi-level perspective framework is used to map the key factors influencing the developments of the blue and green hydrogen export industry in Norway into three analytical levels: landscape, regime and niche-innovations [35]. Landscape factors are exogenous and are beyond the influence of any individual regime or niche actors in the short run [35]. However, changes in the landscape factors can exert destabilising pressures on the regime which creates a window of opportunity for hydrogen-related niche technologies to break into the energy export regime [35]. For this article, the Russian-Ukraine war is arguably one of the most important and relevant landscape factors. It not only impacted the current global energy system, but it also created a window of opportunity for accelerating the energy transition in the EU [36]. In turn, the developments have significant implications for the future development of blue and green hydrogen in Norway.

The regime consists of a system of multiple dimensions that operate semi-coherently under shared norms and practices [35]. These multiple dimensions are interconnected, such that a change in one dimension triggers changes in the others [35]. This article considers both the gas export regime and power regime in Norway as relevant regimes due to the close link with hydrogen technology. The gas regime shares an increasingly intricate relationship with the power regime due to the need for more electricity to decarbonise its offshore activities, produce blue hydrogen and transport and store carbon in geological sites. The power regime, on the other hand, produces electricity mainly from hydropower and onshore wind. Most of the rivers in Norway have been fully exploited, limiting the potential of hydropower for power expansion [27]. Since 2016, the share of onshore wind energy in electricity generation has increased from 1 % to 7 % in 2021, upgrading its status from niche to regime. However, the expansion of onshore wind energy is restrained by the availability of land that does not conflict with local or indigenous interests. Unsurprisingly, gas regime actors tend to be more involved in blue hydrogen export, while power regime actors are more interested in green hydrogen export.

At the niche level, niche-innovations may be defined as technologies that have less than 5 % presence in the analytical regime unit [35]. Their small presence results in the perception that they are not a threat to the regime, allowing developments to occur in a protected space. The growth of niche technologies can be accelerated through the process of linking up to the regime, also known as niche anchoring. This can be done by building more connections which create opportunities for the anchoring to become durable links with the regime [37]. Niche anchoring is more likely to happen if the niche-technology is perceived as symbiotic with the regime [37]. In this case, CCS is a symbiotic niche technology for the gas regime as it helps to maintain its status quo, whereas electrolyser technology shares a symbiotic relationship with the power regime as it enables hydrogen production with electricity. The future of power supply expansion is likely to hinge on offshore wind technology (both bottom-fixed and floating), which falls under the influence of both power and gas regimes as Equinor is the technological leader in Norway for offshore wind.

To understand how the transition pathways of the various hydrogen export routes will unfold, this article employs the exploratory scenario framework to set the parameters of the energy transition process. The framework follows the Intuitive-Logics methodology in which the scenario logics are usually defined in matrices and organised around themes, and equal probability is assumed for each scenario [38]. This approach is useful for capturing complexities in low-carbon transitions that are often overlooked in scenario modelling, which are often techno-economically focused [39]. The scenarios are constructed by intersecting two factors. The first considers the EU's commitment to achieving its climate neutrality goals by 2050, while the second relates to the risks associated with further exploration in the Norwegian Continental Sea. This article takes a climate-neutral EU by 2050 as a departure point, leaving only two possible scenarios that are based on the two possible outcomes of further exploration, as envisioned by the Norwegian Petroleum Directorate: "Expectation" and "Low" [6]. The "Expectation" outcome envisages successful but small discoveries near existing infrastructure, which results in the Business-as-Usual scenario where the petroleum industry is driven by a business-as-usual model. By 2050, gas production will be at half of its peak of 2025 [6]. The "Low" outcome envisages unsuccessful finds of new gas resources in the next two decades, resulting in the Inevitable Transition Scenario, where the petroleum industry is forced into an inevitable transition consisting of downgrading expectations and ceasing exploration by 2040 [6], and turning its focus on developing a market based on hydrogen exports.

In both scenarios, the article draws on the four types of transition pathways from the multi-level perspective framework to inform how the energy transition in each scenario will unfold and how the development of each export route is affected. The four transition pathways are substitution, transformation (partial or full), reconfiguration, or de-alignment and re-alignment. The dynamics of each pathway depend on two criteria: 1) the readiness of the niche-technology at the time of the opening of the window of opportunity and 2) the nature of the relationship that the technology share with the existing regime, whether it is competitive or symbiotic [35]. Table 1 illustrates how the different combination of the two criteria results in different transition pathways. Transitions are non-linear in nature; it is possible to start a pathway with one type and switch to another over time.

To identify the key factors and relevant stakeholders, a document review was conducted on various hydrogen-related peer-reviewed journal papers and reports from established organisations. Eighteen semi-structured interviews were conducted from 2021 to 2023, with hydrogen-related stakeholders to fill in the gaps of information which are not found in documents and to deepen the understanding of linkages between the factors The stakeholders are categorised into five main groups: researchers (3 interviewees), technology experts (2), producers (2 blue & 3 green), policymakers (5), and potential end-users (3). The interviewees were selected through the snowball sampling of hydrogen actors in Northern Norway, where most hydrogen initiatives for export purposes are located. Each interview lasted approximately sixty minutes.

The narratives of the scenarios are created based on the author's understanding and imagination of the possible interactions between the key factors, formed through discussions with the interviewees. The scenarios provide a framework for discussing possible outcomes that can facilitate the planning of mitigation strategies. Nevertheless, a group-process-based approach that captures the consensus of opinions from a larger group of stakeholders in future research may yield deeper insights and contribute to more credible narratives.

Table 1
Transition pathways of the multi-level perspective framework. Adapted from [35].

Transition pathway	Niche technological readiness	Regime-niche relationship	Description
Substitution	Mature	Competitive	Regime actors are overthrown by new entrants from niche actors.
Transformation	Nascent	Symbiotic	Partial reorientation: Regime actors incorporate niche technologies into their business portfolio with little change to the regime architecture. Full reorientation: Full transformation of business portfolio and significant change to regime architecture (full reorientation)
Reconfiguration	Mature	Symbiotic	Symbiotic innovations are originally adopted to solve local problems, then further adjustments are made in other dimensions of the regime such as user practices or technical changes until basic regime architecture is significantly changed.
De-alignment and re-alignment	Nascent	Competitive	Regime collapses due to multiple major internal problems and a regime vacuum arises as multiple niche innovations are technologically immature. Realignment of regime happens when one of the niche-innovations has gained enough momentum to become the dominant technology.

4. Findings and analysis

The first research question is *how might the broader energy landscape in Europe affect the energy export sector and hydrogen export developments in*

Norway? This section will address the question in the next three subsections, each of which presents the key interactions between the different multi-level perspective levels, focusing on the possible impacts on the various hydrogen export route developments.

4.1. Landscape - niche interactions

Hydrogen developments have gained significant traction in recent years, which can be attributed mainly to landscape factors like the establishment of the European Green Deal and the Russian-Ukraine war. The establishment of the European Green Deal and the European Climate Law [40] signals that the fate that Norwegian gas export market will eventually end, and it is only a matter of time. The prohibition of long-term gas contracts extension beyond 2049 under the Hydrogen and Decarbonised Gas Package implies that all EU-bound gas exports will end by 2049 [23]. However, the eruption of the Russian-Ukraine war disrupted the energy landscape and led to the implementation of the RePowerEU, which puts the EU on a two-track transition pathway. The first track tackles energy security issues through drastic reductions in Russian gas supply and diversification of sources through LNG imports, while the second track addresses climate security by ramping up renewable energy in the energy system [1]. The prioritisation of energy security may explain why the EU turned against its Arctic Strategy to leave all fossil fuels in the ground and gave its support for Norway's continued petroleum exploration [5].

The change in EU policy has several implications. First, the petroleum industry benefits from record-high prices which resulted from the diversification of gas supply away from Russia within such a short timeframe. By 2024, the World Bank expects gas prices to remain as high as four times the average between 2017 and 2021 [41] and Equinor estimates that they are unlikely to normalise before 2026 [42]. The combination of high petroleum prices and the EU's support gives the Norwegian government the confidence to aggressively push for continued high levels of petroleum exploration activities. However, the window for hydrocarbon discovery is also closing fast. Considering that it takes on average twelve years to bring petroleum discovery to stream [7], exploration activities need to make a discovery by 2036 or risk being stranded with gas with significantly reduced value. The uncertainty of the future of the petroleum industry is reflected in the decreasing number of production licenses that is offered annually in mature parts of the Norwegian Continental Sea since 2019 [43]. Since natural gas price represents 45–70 % of blue hydrogen production before CCS [44], blue hydrogen exporters in *route 2* who have not secured a long-term gas contract before the Russian-Ukraine war would not be able to compete in the hydrogen trade and may switch to producing green hydrogen earlier than planned. A case in point may be the new partnership of Spanish green ammonia specialist, Fertiberia and Norwegian blue hydrogen producer, Horisont Energi after the partnership with the latter ended with Norwegian petroleum companies, Equinor and Vår Energi in early 2023 [45]. For gas suppliers like Equinor, the high gas prices would make it more attractive to export gas as gas than to export it as blue hydrogen. Consequently, if gas prices continue to remain high, the development of *route 2* may likely be delayed in favour of *route 1*.

Another implication is that the gas market is likely to see more Liquid Natural Gas (LNG) contracts being taken up in the EU. Since the Russia-Ukraine war, the EU has significantly replaced Russian gas with increasing imports of LNG from outside Europe, particularly the USA. In the first eleven months of 2022, Russia's gas market share of the EU's gas imports dropped by almost half, while the USA became the fastest and biggest LNG supplier for the EU [46]. It is worth noting that despite the increase in demand for Norway's gas, the export volume to the EU remains relatively unchanged at around 122 billion cubic meters in 2022 and also for the next few years [47]. This may underscore the maximum capacity of existing gas infrastructure, which limits gas flow increase. The risk of Norway's gas resources from new fields becoming stranded may also increase as new lock-ins are created as new 15-year and 20-year long-term LNG contracts are being signed between the EU and other suppliers [48,49]. As a result, the window for Norway to exploit its new gas resources is rapidly closing. More gas resources may thus become available for blue hydrogen export via *routes 1* and *2*.

Thirdly, the high gas prices have indirectly impacted the electricity prices in the EU due to the dominant use of gas in electricity production. Due to the close connection with EU power grids, electricity prices in Southern Norway have also skyrocketed. Given that electricity accounts for 65–80 % of green hydrogen production cost [9], the green hydrogen exporters in Southern Norway (*route 3a*) may find it difficult to compete with green hydrogen exporters in Northern Norway and elsewhere, where electricity prices are cheaper. This situation is likely to delay the development of *route 3a*. Green hydrogen exporters in Northern Norway (*route 3b*) may however be able to offer more competitive prices than in the EU [11] as the limited transfer capacity between the Northern and Southern power grids has shielded electricity prices in Northern Norway from the geopolitical impacts of the Russian-Ukraine war [10]. As such, green hydrogen exporters in Northern Norway (*route 3b)* have a high chance of being developed than the other routes.

As part of the RePowerEU plan, the EU expects to import 10 million tons of green hydrogen by 2030 to meet its hydrogen demand [1]. As hydrogen can be produced almost anywhere, trade flows are less likely to be threatened by geopolitical events [2]. In the early phase, hydrogen trade is likely to be based on bilateral arrangements [2]. In 2022, the EU signed bilateral agreements on green hydrogen with Morocco, Egypt, Namibia and Kazakhstan [50], but not yet with Norway. However, *hydrogen producers* and *policymakers* mentioned that a few hydrogen production projects in Norway are funded by the EU. Nevertheless, as mentioned above, Germany is exploring the import of blue hydrogen via hydrogen pipelines from Norway [29], which could help boost the development of *route 2a.* Interestingly, before the Russian-Ukraine war, a few interviewees thought that hydrogen pipelines in the short run would be unfeasible as the demand volume was deemed too small to justify the investment.

As part of the European Green Deal, the EU established the EU Taxonomy to define what they consider low-carbon hydrogen. Based on the criteria laid out in the recently-published Delegated Acts of Renewable Hydrogen, green hydrogen produced in Norway with electricity from the power grid will qualify as renewable hydrogen due to the high mix of renewable energy (more than 90 %) of the central grid [51], which favours *route 3*. While the strict definitions of green hydrogen may likely restrict the EU's domestic production of green hydrogen and raise its costs in the short term, the clarity may help to finalise investment decisions and allocation of EU subsidies [52]. A separate ruling for blue hydrogen is expected only at the end of 2024, which adds uncertainty to its business model [52]. *Blue hydrogen producer A* believes that the life-cycle assessment of carbon emissions will make it challenging for blue hydrogen produced from gas extracted from new fields to qualify as low-carbon hydrogen. *Blue hydrogen producer B* has not ruled out using gas from new fields but was concerned about the validity period of the current definitions and the possibility of stricter thresholds being imposed by 2030. In general, the EU prefers green hydrogen to blue hydrogen due to the scepticism towards CCS and the continued reliance on gas (*policymakers*). Further, green hydrogen is perceived to contribute to more energy independence and create more jobs in the EU (*producers*). Considering this, the window of opportunity for exporting blue hydrogen via *routes 1 and 2a* would be dependent on how long existing gas resources would last. *Route 2b* could still be used for exporting blue hydrogen gas to other parts of the world with less stringent rules about carbon emissions, but the prices would have to be competitive with other blue hydrogen-producing countries.

4.2. Regime - niche interactions

Since Norway's oil production peaked in 2001, the government became increasingly interested in extending its hydrocarbon frontier towards the north, particularly in the Barents Sea [53]. The Barents Sea is estimated to hold 65 % of the remaining undiscovered resources and it is associated with higher extraction costs and risk of failure due to unexplored geology and limited infrastructure [6]. The average discovery rate for commercial fields has been declining and in 2017–2021, the commercial success rate was below 30 % and the average exploration cost per well was around 592 billion NOK [54]. The risks associated with undiscovered resources are higher as they have not been proven through drilling, they represent almost half of the remaining gas resources at the end of 2021 [54]. According to the "Low" scenario of the Norwegian Petroleum Directorate 2022 Resource Report, which expects no discoveries to be made, oil and gas production will reduce to almost zero by 2050 [6]. Under the "Expectation" scenario, where discoveries are expected to be made along the existing infrastructure, the volumes are not expected to be significant, resulting in an estimated 70 % decline compared to 2022 by 2050 [6]. Given the dependence on gas for its production, blue hydrogen export (*routes 1* and *2*) would follow the same trend under both scenarios.

Despite being the third largest gas exporter (behind Russia and Qatar) in 2021 [3], Norway prides itself as an environmental leader, being one of the first countries to introduce carbon tax (1991) and having one of the greenest electricity production. As part of the Paris Agreement, Norway introduced the Climate Change Act in 2018, which makes its emission reduction targets legally binding [55]. The targets for 2030 and 2050 are a reduction of at least 55 % [56] and 90–95 % [57] respectively, compared to 1990. To meet these targets, Norway intends to decarbonise its petroleum sector, which accounted for about a quarter of Norway's carbon emissions in 2020 [58] through electrification. The power supply should to a large extent come from offshore wind technology or other renewable energy produced in the Norwegian Continental Sea [59]. However, Statnett does not expect offshore wind technologies to be ready before 2030 [60]. Meanwhile, Equinor intends to electrify its LNG facility in Northern Norway with power from the mainland grid [61], which necessitates a new power line to be built that could adversely affect the indigenous Sami people's culture of reindeer herding in the region [62]. Equinor estimated that using CCS would cost three times more than electrification [62]. If Equinor proceeds as planned, the development of *route 3* would be limited or delayed due to the lack of renewable energy.

Most of the power supply in Norway is generated by hydropower and onshore wind, managed by Statnett and the Norwegian Water Resources and Energy Directorate [27]. Both organisations report to the Ministry of Petroleum and Energy. In 2022, the power surplus in Norway stands at around 17 terawatt hours, contributed by both Northern and Southern Norway [60]. With the power demand expected to rise faster than the production increase in the next few years, Norway may face a power deficit by 2030, especially in Southern Norway [60]. The power demand increase is due to further electrification (particularly of the offshore platforms), whereas the sluggish production growth may be attributed to local resistance against onshore wind farms and the nascent state of offshore wind technology [60]. Power prices in both Southern Norway and the EU are expected to increase due to the close grid connection and reduce blue hydrogen production via *routes 1* and *2a* as the associated carbon storage process is said to be energy-intensive [16]. Statnett estimates that offshore bottom-fixed wind will be installed from 2035 onwards and contribute to a power surplus in Southern Norway [60]. However, Northern Norway will start to have a power deficit from 2040 onwards due to increased power demand and limited opportunities for power production growth [60]. The resistance towards onshore wind developments may be attributed to the lack of clarity in the political goals and engagement to address the environmental and social consequences of wind power [63]. Assuming stagnant growth in onshore wind, the future of *route 3b* hinges heavily on the development of floating offshore wind technology, which is unlikely to mature before 2040 and may face potential resistance from the fishery sector [60]. Furthermore, a delay in offshore wind development, both bottom-fixed and floating, will jeopardise the development of *route 3*.

4.3. Niche-niche interactions

Before the hydrogen trade market between Norway and the EU is established, the domestic hydrogen market is vital for hydrogen production in Norway to scale up. In Northern Norway, hydrogen is perceived as better suited as a transport fuel compared to batteries in Northern Norway because of the cold temperatures (*locals*). While there were concerns about the leakages and explosions, the general attitude towards hydrogen was rather positive and focused on the new opportunities that may benefit their communities (*locals*). The positive attitude of interviewees towards hydrogen may be that none of the hydrogen projects is operating yet and there has been little day-to-day interaction with the technology to understand the full safety implications (*policymakers and locals*). Interviews with *policymakers and locals* showed that most people in Norway have limited knowledge about hydrogen, as confirmed by a recent survey [64]. However, when people are informed about the various hydrogen production methods, there was a stronger preference for green hydrogen [64]. As more people know about hydrogen and green hydrogen prices fall, domestic green hydrogen demand in Norway will likely dominate and contribute to the development of *route 3*.

However, Norway is perceived as lagging in its Hydrogen Strategy are perceived, compared to the EU, as most funding is dedicated to continued research and concept development rather than providing more support at the implementation stage (*producers*). G*reen hydrogen producer A* believes that the hydrogen market will develop faster if given the same level of government support for battery-operated electric cars, such as a massive rollout of infrastructure and generous tax reliefs. Norway currently has the world's highest number of electric vehicles per capita in 2022 [65]. The lag in support could be attributed to the predefined role in Norway's Hydrogen Roadmap for blue and green hydrogen, where the former will cater to industrial applications and exports and the latter is restricted to small-scale applications [8, p.107]. This pre-defined mix was justified by the lower production cost and scalability of blue hydrogen relative to green hydrogen [66]. However, this argument seems weak when compared to Europe's ambition to build green hydrogen plants at a gigawatt scale. The dominant role of blue hydrogen may be linked to the petro-industrial complex in Norway [27] and the symbiotic relationship between blue hydrogen and the gas regime. Against this background, *route 1* and *2a* are more likely to benefit. While blue hydrogen and CCS seemingly share a symbiotic relationship, it is interesting to note that the development of blue hydrogen may limit the growth of CCS as a stand-alone service as the latter would only be required if the equipment runs on fossil fuel like gas (*experts*). If companies switch to using hydrogen as a fuel, then there will be no emissions to reduce.

Furthermore, Equinor estimated that CCS would cost between 450 and 600 Euros per ton carbon dioxide equivalent (EUR/tCO_2e) [62], which seems significantly higher than the estimates given by other studies (between 98 and 254 EUR/tCO_2e) [67]. One of the interviewees, *CCS expert A* estimated that the carbon tax needs to be at least 130EUR/tCO_2e for CCS to be economically feasible. If Equinor's cost estimations are correct, blue hydrogen cost and the financial viability of *routes 1* and *2* would be put in question. Also, additional costs are incurred to build infrastructure for carbon transport from the EU to Norway in the case of *route 1* as it does not exist today. Nevertheless, *blue hydrogen producer B* and the Ministry of Petroleum and Energy insisted that blue hydrogen is more cost-effective than green hydrogen, despite reports of green hydrogen being more affordable due to the high gas prices in 2021 [2,66]. Even if gas prices drop to pre-war levels, green hydrogen production cost is expected to be cheaper than blue hydrogen by 2030 as electrolysers are relatively new and have more potential for cost reduction, whereas blue hydrogen production method is more mature [9]. Furthermore, gas prices are driven by global market forces and tend to be more volatile, whereas electricity price variations can be managed regionally through renewable energy expansion in the energy system [68].

One of the biggest challenges faced by both *blue and green hydrogen producers* is getting customer orders, related to the "chicken-or-egg" dilemma. Several of the interviewees cited the importance of customer orders to get the final investment approved (*producers and experts*). Customers may be reluctant to commit because existing machinery needs to be modified or new designs are needed before hydrogen can be used. For *end-user B*, affordability and supply security are important considerations for adopting hydrogen-related technologies. *Policymaker A* cited the need for more collaboration with manufacturers in the transport and maritime sector to overcome this problem, in line with the *producers'* view that the hydrogen industry needs to take the lead to work on building both the value chain and the market in parallel. Both *blue and green hydrogen producers* agree that they need to work together to build the industry up. Since all the *blue hydrogen producers* interviewed have plans to switch to producing green hydrogen at some point, green hydrogen export via *route 3* could be the long-term dominant export route if developments take place within the window of opportunity.

Table 2 summarises the key factors that influence the various hydrogen export routes at the different multi-level perspective levels. The next section will discuss how these interactions will play out in the two scenarios: Business-As-Usual and Inevitable Transition.

5. Exploration of scenarios

This section addresses the second research question: *what might be the implications of the outcomes of further petroleum exploration on hydrogen export developments in Norway?* To understand how the different outcomes of petroleum exploration will impact low-carbon hydrogen export developments in Norway, the article is essentially interested in the interactions between the regime and the niche, and how they might differ in each scenario. Fig. 2 illustrates how the gas production trajectory may look under the Inevitable Transition and Business-As-Usual scenarios.

5.1. Business-as-usual scenario narrative

Under the pressure to meet its climate change targets, the Norwegian government and the gas regime plan to electrify its offshore platforms to reduce its carbon emissions. The power should be sourced from offshore wind energy as much as possible [59], but the roll-out of the technology is not expected before 2030. In addition, the threat of a fast-declining demand for its gas exports has urged the government to allocate more funding for CCS and blue hydrogen [69], which can help enhance the value of gas. Both the electrification of platforms and the inclusion of new niche-technologies in its portfolio, while keeping the basic architecture of the regime intact, suggest that the gas regime is currently on a *partial reorientation pathway* [35].

In the Business-As-Usual scenario, small gas discoveries are expected along the existing infrastructure. In December 2022, Vår Energi discovered a new oil field in the Barents Sea, which is co-owned with

Table 2
Summary of the impacts on hydrogen export routes in Norway from a multi-level perspective.

Export route	1	2a	2b	3a	3b
Hydrogen type	Blue	Blue	Blue	Green	Green
Export method	Gas pipelines	Hydrogen pipelines	Ammonia tankers	Hydrogen pipelines	Ammonia tankers
Region in Norway	South	South	North	South	North
Landscape – niche interactions					
High gas prices	Little impact for exporters but gas exports are more profitable	Without a long-term gas contract signed before the war, exporters are likely to switch to green hydrogen production earlier.			
LNG imports	More gas available for production after 2049				
High electricity prices	May affect blue hydrogen production costs and CCS costs			Possible delay in development due to connection with the EU	Relatively unaffected due to limited transfer capacity
Hydrogen import demand from EU by 2030		Germany-Norway collaboration may boost this	Support via EU funds but no bilateral agreements yet		Support via EU funds but no bilateral agreements yet
EU Taxonomy & Delegated Acts (DA)	DA for blue hydrogen is expected only at end of 2024. Uncertainties for investors prevail.			Helps to finalise investment decisions and allocation of EU subsidies. EU domestic production may be limited due to DA rules.	
Regime – niche interactions					
Depleting gas reserves	«Low» scenario foresees zero blue hydrogen production by 2050; «Expectation» scenario foresees blue hydrogen production to be significantly reduced by 2050.			Pro-petroleum policies may divert needed resources to develop green hydrogen production.	
Increased electrification of offshore platforms	Power supply will likely come from onshore power until offshore wind is available from 2035 onwards.	New power lines may be needed and may have social and environmental consequences		Lack of power supply may delay the development of green hydrogen production.	
Power deficit in Southern Norway 2030-2035; Power deficit in Northern Norway 2040-2050	Lack of power supply before 2035 may reduce blue hydrogen production in Southern Norway.		Lack of power supply after 2035 may reduce production.	Development may be delayed until after 2035. Development hinges on the roll-out of offshore bottom-fixed wind farms.	Production may stagnate by 2040 unless onshore wind resistance is overcome, or offshore floating wind technology matures.
Niche-niche interactions					
Positive perceptions of hydrogen	Blue hydrogen demand may drop as end-users become more informed about various hydrogen types			Stronger preference for green hydrogen among informed end-users	
Norway Hydrogen Roadmap: Pre-defined roles	More governmental support due to petro-industrial complex.			Reduced role to small-scale applications may limit developments.	
High estimates of CCS cost & High potential for cost reduction in green hydrogen production	Financial viability of blue hydrogen production is put in question and CCS infrastructure developments may be delayed	Financial viability of blue hydrogen production is put in question.		Less susceptible to global price volatility and even if gas prices drop, green hydrogen production cost is expected to be cheaper than blue hydrogen by 2030.	
New market: Chicken-and-egg dilemma	Strong collaboration between both blue and green hydrogen producers in building value chain. All blue hydrogen producers expect to switch to green hydrogen at some point.				

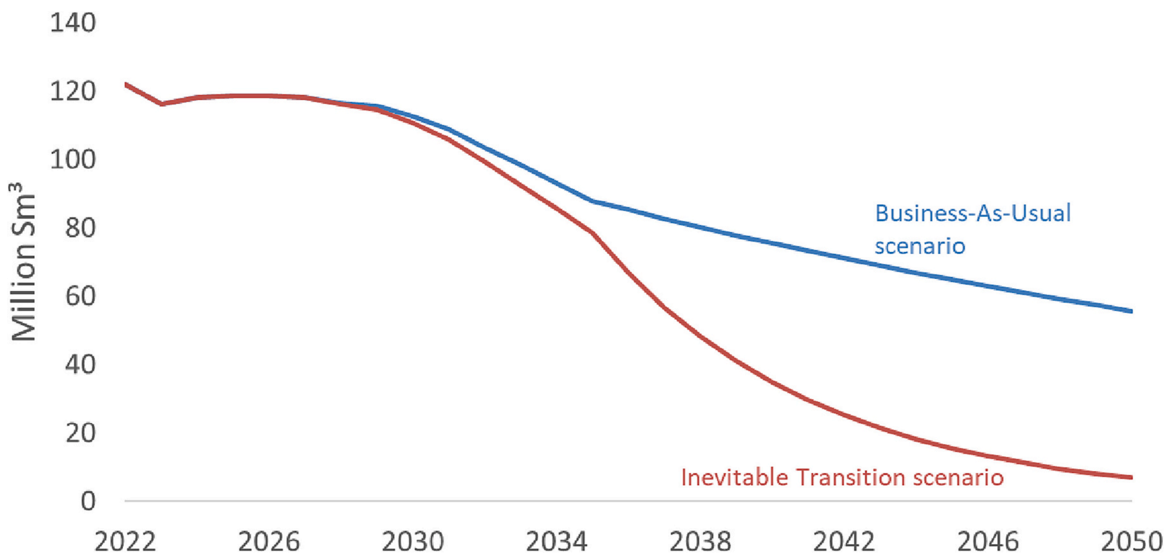

Fig. 2. Author's illustration of gas production trajectories based on the outcomes projected by the Norwegian Petroleum Directorate Resource Report 2022 [6].

Equinor [70]. Assuming the average 12-year lead time, the discovery will only come to stream from 2034 onwards. In the period before that, competition for gas resources may intensify between Norway-based blue hydrogen exporters and EU-based Norwegian blue hydrogen exporters, namely Equinor. Given the company size and the likelihood that gas prices will remain high until 2026 [42], it is likely that the latter will prevail (*route 1)*, whereas the former (*route 2*) may have to switch its focus to green hydrogen export (*route 3*) sooner than planned.

Although most blue and green hydrogen producers interviewed expect operations to be ready by 2025, exports to the EU are unlikely to happen before 2030 given the small volumes projected in the RepowerEU plan [1]. Therefore, between 2025 and 2030, the hydrogen supply may initially be focused on fulfilling domestic demand, before diversifying to hydrogen exports to the EU in 2030 [1]. By 2030, IRENA expects electrolyser costs to fall so significantly that green hydrogen costs will be lower than blue hydrogen [2]. However, the green hydrogen production volumes in Norway are likely to remain small as the power supply is used up for the electrification of offshore platforms [60]. Consequently, this may prevent the development of *route 3*.

In anticipation of the imminent decline of gas exports to the EU, as mandated by the European Green Deal to end all gas contracts by 2049, the gas regime may undertake a *full transformation pathway* in 2040 to make way for blue hydrogen exports. However, it remains to be seen if blue hydrogen produced from gas found in new fields would qualify as low-carbon hydrogen under the upcoming Delegated Acts for low-carbon hydrogen. If the blue hydrogen is compliant with the EU taxonomy, the gas regime would be able to valorise the remaining gas reserves at the end of 2050 and export blue hydrogen via *route 2*. In the event of non-compliance, the gas regime could consider exporting gas in the form of LNG to countries beyond the EU. However, Norway may find it challenging to compete, in terms of prices, with other major LNG exporters in the global market. Hence, there is a risk that Norway would end up with stranded gas reserves.

5.2. *Inevitable transition scenario narrative*

The starting point of the Inevitable Transition scenario is the same as Business-As-Usual, where the gas regime undertakes a *partial transformation* pathway. Blue hydrogen exports via *route 1* are likely to prevail in 2030 as *route 2* blue hydrogen exporters may find it difficult to secure a stable supply of affordable gas, while *route 3* green hydrogen exporters may not be able to scale up due to a lack of affordable power supply.

Unlike the Business-As-Usual scenario, the Inevitable Transition scenario envisages a continuous decline in gas production due to the lack of discoveries. By 2040, investors may start to lose faith in the regime and start pulling out their investments. Employees in the gas regime may start looking for alternative job opportunities in other sectors. Eventually, this leads to a regime collapse, as prescribed by the *de-alignment and re-alignment pathway* [35]. *Routes 1* and *2* are severely affected due to the lack of gas for production. Green hydrogen exporters (*route* 3) are unable to step up and fill in the vacuum left by the gas regime as most of the government resources are assumed to have been dedicated to offshore exploration, depriving them of the necessary support to scale up.

If the plans for offshore bottom-fixed wind proceed as projected by Statnett [60], a power surplus will likely result as offshore platforms are decommissioned and require less electricity. Assuming that the power supply from the offshore wind is connected to the onshore grid, there may be a possibility for the surplus electricity to be exported to the EU. If a climate-neutral EU is assumed in 2050, it is also likely that the EU would have achieved its binding EU-level target of 40 % of renewable energy in its energy mix by 2030 [71]. By 2040, the mix of renewable energy is expected to be higher, limiting the volume of electricity exports. Hence, the regime vacuum left by the collapse of the gas regime is expected to last as long as the time it takes to build the infrastructure needed to scale up green hydrogen production, which may take up to 10 years for the energy export regime to be *re-aligned*. When that happens, green hydrogen exporters (*route 3*) can rise to dominance.

Although it is widely expected that the phase-out of petroleum exports will entail a slowdown in economic growth, previous research showed that the growth could be maintained through hydrogen exports [16]. However, this requires early planning of the phase-out and major restructuring of Norway's economy. In this scenario, failing to plan early would result in delaying the scaling-up of green hydrogen production in Norway and losing its competitiveness to other green hydrogen exporters. Further, other green hydrogen exporters may have had locked-in EU with their long-term contracts by the time Norway is ready to export, denying Norway the chance to become a major green hydrogen exporter.

6. Discussion and conclusion

While the Russian-Ukraine war has undeniably accelerated the energy transition process in the EU, it has somewhat contributed to a delay in the phase-out of the petroleum sector in Norway. The resulting high gas prices and electricity prices have enabled Norway to reap high profits at a national level, although at the expense of its residents in Southern Norway. Further petroleum exploration entails risks, not only from a climate perspective but also from an economic and social perspective. The continued use of fossil fuel that results from successful explorations will result in carbon emissions despite the electrification of offshore platforms. From a global climate perspective, there is no place for more carbon emissions in the carbon-constrained world we live in today.

Norway's ambition to extend the life of the petroleum sector is comprehensible, but the analysis above suggests that the risks outweigh the gains. First, the risk of unsuccessful finds is high and costly. Second, even if discoveries were made as projected by the "Expectation" scenario of the Norwegian Petroleum Directorate, the trajectory of the gas production levels will still decline by at least half compared to 2022 by 2050. This indicates that there is still a need for a phase-out plan for the petroleum sector to prepare Norway for a climate-neutral Europe in 2050.

Assuming that the EU achieve its climate targets, the value of the remaining gas reserves in the Business-As-Usual scenario in 2050 is put in question as the EU will cease its imports from Norway. To reach other markets, Norway could turn to the LNG market, which entails higher production costs and more intense competition with other suppliers. The next alternative is to transform gas into blue hydrogen, which can then be exported to the EU via repurposed or new hydrogen pipelines (*route 2a*). However, there may be a few barriers to overcome. First, the establishment of the Delegated Acts for low-carbon hydrogen is only expected at the end of 2024 and this could deter investors from funding blue hydrogen projects. Second, the production cost of green hydrogen is expected to be lower than blue hydrogen by 2030, making it difficult for blue hydrogen exports to compete with green hydrogen exports in 2050. Third, studies showed that when the public is more informed about the different types of hydrogen, they are more inclined to choose green hydrogen. As such, blue hydrogen exporters in Norway may likely have a window of opportunity between 2025 and 2030 to exploit *route 2a*.

Based on the findings in Section 4, *route 1* has the highest potential to be the dominant export route, given the symbiotic relationship it shares with the gas regime. At the same time, the production trajectory is likely to decline as gas production falls over time due to the use of gas as feedstock. High gas prices are expected to last till 2026 and since they account for the bulk of blue hydrogen production costs, the development of *route 1* may face some delays. In addition, the high costs of CCS and the lack of carbon storage and transport from the EU to Norway may hinder the further advancement of *route 1*. For blue hydrogen exports to play a role in a post-petroleum society, *route 2* is expected to bring in more social benefits than *route 1* as the location of the hydrogen production plant determines where job opportunities will be created.

In both Business-As-Usual and Inevitable Transition scenarios, the Norwegian government is assumed to invest heavily in supporting the petroleum sector, which leaves fewer resources for the development of green hydrogen production (*route 3*). As the Inevitable Transition scenario shows, the failure to support the scale-up of *route 3* could potentially result in a regime collapse. This may lead to not only the loss of faith in the gas regime but also to reduced confidence and trust in the government's ability to secure a post-petroleum future. Due to uncertainties during the regime vacuum, significant economic and social repercussions may occur. While Norway can attempt to catch up, it may be too late as other green hydrogen exporters may have locked in the EU's hydrogen demand with long-term contracts. The Inevitable Transition scenario illustrates that a delay in the early planning of a petroleum phase-out could have dire consequences for a post-petroleum Norway.

Further, increased electrification will quickly turn the power surplus in Norway into a power deficit. The limited electricity supply will lead to higher electricity prices and reduce the competitiveness of new green industries, including blue and green hydrogen. There are two main ways to increase the power supply in Norway in a short period. The first is to reduce power consumption by improving energy efficiency and reducing power usage. More stringent rules on energy efficiencies and government incentives, as well as reduced energy use in offshore platforms, could help to unleash more power needed to scale up green hydrogen (*route 3*). Second, the government needs to find new strategies that overcome the local protests against onshore wind farms. Studies suggest that such opposition may be resolved through the early involvement of all relevant local stakeholders in new development projects and through reframing them in local benefit terms like industrial developments or addressing their concerns on the environmental impacts [63,72].

Regardless of the political will to transition, the finite nature of fossil fuels guarantees a certain post-petroleum future for any fossil exporters. Low-carbon hydrogen could play an important role in facilitating a smooth energy transition to a post-petroleum economy, but only if action is taken in time during the window of opportunity. To avoid a hard landing and secure its position as a key trading partner with the EU, Norway needs to start its energy transition without further delay. This also applies to other fossil export countries that are still lagging in the race to transition. The European Commission estimates that the transformation of an industrial sector and all its value chains will take 25 years [73]. This implies that actions and policies for a *full transformation* pathway need to take place in Norway by 2025 to be ready for a climate-neutral Europe in 2050.

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.

Data availability

The data that has been used is confidential.

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