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Options for CO_2-lean hydrogen export from Norway to Germany

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ABSTRACT

Norway is a nation with an abundant supply of energy, both from fossil and renewable resources. Due to limited domestic demand, Norway is today exporting large amounts of petroleum products. For the future, various options for export of CO_2-lean energy exist, both from Northern and Southern Norway, and both from fossil sources (including carbon capture and storage), and renewable energies (particularly wind power). Transport vectors are hydrogen pipelines, liquid hydrogen ships and HVDC cables, and a plausible customer is central Europe due to its proximity, high population density and lack of domestic energy resources.

Within the framework of the "NorWays" project, various options to deliver energy for hydrogen-based transportation from Norway to Germany were studied. Eight CO_2-lean well-to-wheel energy export chains were evaluated with respect to efficiency, GHG emissions and other environmental impacts, costs and utilisation of Norwegian R&D experience. In the chosen scenarios, energy export via hydrogen pipelines and ships appeared energetically and economically interesting against existing approaches as NG and electricity export. Furthermore, increased utilisation of Norwegian R&D experience and higher value creation is anticipated by the export of a higher refined product.

1. Introduction

Norway is currently the largest energy producer and exporter in Europe. While the oil production has already reached its maximum in year 2000 and has decreased by as much as 20% since then [1], large resources of natural gas (NG) are still available, and the domestic utilisation of NG is very limited. Practically all NG is exported (97%), and nearly all by the network of pipelines from the North Sea to the European continent. Furthermore, there is a vast amount of unexploited renewable energy resources, especially in terms of substantial wind energy potential. Average wind speeds in Norway, both on- and offshore, exceed by far those found in Denmark, Germany and Spain where wind energy initiatives and investments are predominantly driven by political incentives. In addition Norway has a huge storage potential for CO_2 in sub-sea aquifers to mitigate climate damage. The storage capacity is estimated to 70 years of Europe's current CO_2-emission [2].

In view of the recent focus on climate change, there is definitely a great interest in increasing the share of renewable power for most European countries. Norway has electricity transfer capacity to Sweden, Denmark, Finland and Russia; the former being the largest (approximately 3600 MW). The amount of energy that can be transferred between Norway and the neighbouring countries is limited to around 20 TWh/year. In addition, a sub-sea, high-voltage direct current (HVDC) cable to the Netherlands is under construction, with a capacity of 600+100 MW (from 2008) [3], and a similar cable to Denmark is approved. If hydrogen is to become an important energy carrier for the future, a huge demand for CO_2-free or -lean hydrogen will arise. Thus, large-scale export of CO_2-lean energy, namely electricity or hydrogen, to continental Europe may become a very interesting option in addition to NG transport and electricity transmission. Different authors have studied the basic feasibility of long-distance hydrogen transport corridors in the past [4–10]. Also hydrogen export from Norway's abundant renewable energy

Abbreviations: CCGT, combined cycle gas turbine; CCS, carbon capture and storage; CGH_2, compressed gaseous hydrogen; EOR, enhanced oil recovery; GHG, green house gas; HVDC, high-voltage direct current; LH_2, liquid hydrogen; LHV, lower heating value; LNG, liquefied natural gas; NG, natural gas; SMR, steam methane reforming

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sources has been studied previously [9]. In that work, the production of hydrogen from hydro-power stations in the North of Norway, together with liquefaction and shipping to German ports was considered and comparisons to direct electricity transmission were performed. It was concluded that due to the limited excess hydropower, the export system may only be for demonstration purposes.

Wietschel and Hasenauer [10] have investigated renewable hydrogen corridors and compared long-distance hydrogen transport from energy-rich countries to population centres against hydrogen production from local sources in the population centres. Also here, Norwegian hydropower has been studied and came out as the second cheapest renewable hydrogen option. Export of hydrogen from NG was believed not to be economic against NG export, however, not considering the potentials of CO_2 sequestration in Norway.

Since the previous studies, wind power has become economically interesting and the untapped potential is higher than for hydropower, and also interest in CO_2 sequestration has increased. Therefore, this paper attempts an evaluation of options for large-scale wind and CO_2-lean NG energy export from Norway to Northern Germany. Wind energy and NG from two different locations are considered, and for each option two transport chains are compared with respect to efficiency and green house gas (GHG) emissions. Furthermore, a comparison of estimated costs is made based on current technology forecasts. A qualitative assessment of the existing technological expertise in Norway, feedstock flexibility, end-use flexibility and other environmental impact is also included. The study was performed within the framework of a Norwegian publicly funded national hydrogen roadmap project entitled "NorWays" [11].

2. Framework, methodology and assumptions

2.1. Methodology and analysis framework

This study assesses direct specific energy use (i.e. energetic efficiency), GHG emissions and costs of a number of energy chains for large-scale export of renewable energy from Norway to Germany. Each energy chain consists of various linked processes representing the necessary energy transport and conversion steps. The E3database tool [12] was used for all calculations. E3database is a tool to assess energy chains with respect to energy use (from source-to-user), emissions and economics/specific costs. The tool has been used in different well-accepted European studies [13,14].

Energy sources are wind electricity (on- and offshore) and natural gas. For each source the direct export of the electricity or natural gas with subsequent hydrogen production is compared with the transport of hydrogen. End product for all energy chains is hydrogen delivered at a central terminal in Northern Germany (e.g. Hamburg) for further distribution and use as a transportation fuel.

For all export energy chains, large-scale production and transport (1–4 GW[1] hydrogen output) is assumed. The economies of scale differ between the technology options;[2] hence the components used for the options studied here have individual capacities that match their typical economic optimum scale. This represents to some extent the integration of the energy chains into the energy system rather than tunnel-like point-to-point connections.

The chosen timeframe is year 2020–2030, when a fully developed demand for hydrogen energy in Europe is assumed [13,14]. The cost estimates are based on currently available forecasts and despite being highly uncertain, they provide indications for the economic requirements for the installations under consideration. Full utilisation of the equipment capacity is assumed.

For the chains using energy resources from Northern Norway, the end-product is liquid hydrogen (LH_2) and for the chains using energy resources from Southern Norway, it is compressed gaseous hydrogen (CGH_2) at 20 MPa for pipeline or gas trailer delivery. The need for hydrogen in both these conditions is assumed; gaseous for short-distance distribution by pipelines, and liquid for long-distance distribution by truck. Therefore, neither liquefaction of the CGH_2 nor evaporation of the LH_2 is foreseen.

To avoid a strong economic impact of CO_2 prices, but still facilitate a fair cost comparison, it is assumed that all chains are CO_2-lean[3] or virtually CO_2-free. This implies that carbon capture and storage (CCS) technology is feasible (at 85% CO_2 recovery) within the considered timeframe [16], and that sufficient CO_2 storage capacities are available both in Northern Germany and in Norway [17]. The residual emissions are taxed implying minor cost.

The possibility to use the CO_2 for enhanced oil recovery (EOR) has not been considered due to recent findings by Shell Norway and Statoil that EOR with captured CO_2 does not seem economically viable [18]. Likewise, interaction with the existing energy system (such as increasing the capacity factor of transmission lines by integrating existing hydropower reservoirs) has not been accounted for, since this would require a dynamic grid simulation model [19,20]. Further, a complete life-cycle assessment (i.e. accounting grey energy and emissions associated to equipment production, as well as environmental impacts beyond GHG emissions) has not been performed here; only direct energy use, emissions and costs have been accounted.

The following sections elaborate on the potentials of the considered energy feedstock, the chains considered and the techno-economic assumptions for the analysis.

2.2. Energetic potentials of the considered feedstock

2.2.1. Onshore wind in Northern Norway

The overall potential for wind energy utilisation in Norway is very high, due to high wind speeds and furthermore low population density and thus few exclusion areas. A total theoretical potential of 900 TWh/a has been estimated by Hofstad [21]. The same author [22] has estimated that from all onshore areas that are available and potentially economically viable for use of wind energy (i.e. >7 m/s average wind speed), an amount of 245 TWh could be produced annually, 163 TWh, of which is in Finnmark, the northernmost county of Norway. Under the used cost assumptions, 150 TWh could be produced at specific costs not higher than 4.4 $ct_€$/kWh. Thereof, including a potential minor export to Finland, only approximately 0.9 TWh/a can be adapted by the current grid without substantial investments for upgrading transmission lines.

2.2.2. Offshore wind in Southern Norway

A theoretical physical potential of 180 TWh/a for areas with less than 10 m water depth, and 829 TWh/a for water depth up to

[1] Where applicable, energy and power specifications in this study are based on the lower heating value (LHV) of the fuels.

[2] For example, the technical maximum of single HVDC sea cable capacity seems to be 1–2 GW, and beyond that no significant specific cost degression can be achieved by further upscaling. In contrast, pipelines have stronger economies-of-scale in this size [15].

[3] CO_2-lean implies that carbon capture and storage be applied to the main conversion processes. This mitigates green house gas emissions, but does not totally eliminate them, because only about 85% of the CO_2 is captured and furthermore due to distributed emissions (e.g. from use of grid electricity).