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Direct air capture (DAC) deployment: National context cannot be neglected. A case study applied to Norway

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ABSTRACT

DAC deployment is still an open question. Recent publications focused on energy consumption and the relationship between the cost of captured CO_2 and operating conditions. These works addressed a preliminary assessment of the best locations but neglected the importance of the local context to succeed in implementing DAC in a specific country. Certainly, levelized costs provide a pointer of the costs but do not point out the impact on the natural resources to be allocated (land use and energy) or if the energy consumption outweighs the environmental benefit. Furthermore, it does not consider if it clashes with planned national strategies. This article aims at predicting the impact of DAC facilities deployment in the Norwegian context by taking advantage of international reports by independent agencies. The estimates are just preliminary but offer an initial rough estimate of Direct Air Capture (DAC) technologies deployment at a national level taking the local resource consumption into account.

1. Introduction

1.1. Environmental contingencies and planned actions

The UN environmental agenda ambitiously targets to cut global greenhouse gas (GHG) emissions by 30 % or 45 % by 2030 and achieve net zero by 2050. The different rates in cutting the emissions depend on the strategy that we would like to follow by keeping the temperature raise below either 2 or 1.5 °C, respectively. If the first scenario was the target, the first milestone aims for downshifting from the current 52 Gt_{CO2}/y to 32 Gt_{CO2}/y within seven years. This strategy is incentivising the deployment of carbon capture and storage/utilization (CCUS) solutions and the development of novel disruptive carbon dioxide removal (CDR) technologies (“Emissions Gap Report 2022,” 2022; “Net Zero by 2050 - A Roadmap for the Global Energy Sector,” n.d.). In 2022 global energy-related and industrial processes CO_2 emissions reached a new peak of 36.8 Gt_{CO2}/y (“CO2 Emissions in 2022 – Analysis,” 2023).

1.2. CDR: Technologies and need for policies

The CDR technologies portfolio includes several alternatives (Hepburn et al., 2019; Terlouw et al., 2021), such as direct air carbon capture & sequestration (DACCS or simply DAC), bioenergy and carbon capture & storage (BECCS), mineralization, afforestation, and biochar. Among these, direct air carbon capture, DAC, is gaining interest and attracting investments (Direct Air Capture 2022 *A key technology for net zero*, 2022; IEAGHG, 2021a; Lebling et al., 2022; National Academies of Sciences and Medicine, 2019). Currently, the adsorption technology used by companies such as Climeworks and Global Thermostat as well as the absorption-based approach used by, for example, Carbon Engineering are the only ones close to industrial deployment. Current TRL ranging for these are 7–9. When a balance is drawn, DAC looks to be the most promising solution due to several reasons. Although DAC is an energy-intensive CDR solution, it allows to permanently store captured CO_2 into a reservoir and the process can be done in confined space. Indeed, IEA showed that to capture the 8 Gt_{CO2}/y from the atmosphere BECCS and afforestation require 160 and 405 times the land occupied by DAC facilities (IEAGHG, 2021a). As mentioned, afforestation and BECCS demand for large onshore land, but these options are no energy-demand. Afforestation can instead provide the feedstock for BECCS and the Global CCS Institute reports that Scandinavian area has a good potential for afforestation heat-power bioenergy applications (Bright et al., 2020; Consoli, 2019). Cherubini et al. pointed out that afforestation can be a good CDR solution for isolated areas and this “technology” enables to

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recover land not suitable for any human activities (Næss et al., 2023). Mineralization allows storing CO_2 in the form of carbonates, and it is a form of permanent storage. Experts state that mineralization is the fastest way to reach net-zero emissions (Rosa et al., 2022) or positive carbon mitigation when combined with DAC (Kelemen et al., 2020). However, the water consumption is quite relevant from 1.5 to 8 kg_{water}/kg_{CO2} (Direct Air Capture 2022 *A key technology for net zero*, 2022; IEAGHG, 2021a). An alternative path to the storage and/or mineralization is the utilization, but this option is still under investigation because it is energy starved. A recent publication showed that utilization of CO_2 from DAC has a negative impact because still emits GHG (Deutz and Bardow, 2021). However, utilization needs more efforts to make this alternative economically viable and appealing (Mertens et al., 2023; Roh et al., 2020). Günther and Ekardt emphasize that CDR activity will contrast with human rights such as the access to water, land, and electricity; thus, there should be a balance between these rights and climate actions (Günther and Ekardt, 2022). As a matter of fact, there is not a unique recipe to address net-zero emissions and all nations are expected to take actions accordingly based on resources availability (Lee et al., 2021) and minimize the impact of the demand for natural resources (Fuhrman et al., 2020). Currently, Norway is more active in BECCS deployment and industry decarbonization through carbon capture technologies and investments in the hydrogen production, while DAC is still under investigation. Despite Norway has been a pioneer country in carbon capture and sequestration (CCS) and climate change mitigation ("Carbon Capture, Utilisation and Storage - Energy System," n.d.; "Tracking Clean Energy Progress 2023 – Analysis," n.d.; Consoli, 2019; van Alphen et al., 2009), the debate on CDR technologies is still open and there is a huge excitement around these options not only in terms of investments, but also opportunity to accelerate the decarbonization and net-zero emissions target ("SV vil støvsuge CO_2 fra luften," 2023).

Some technologies look to be close to their maturity, others are still at an early stage of development. Policies will cover a key role in enabling development and the deployment of CDR solutions. Experts show that there are different levels where policy makers must act: support and incentives to CDR research, implementation of a more heavy taxation of the CO_2 emissions and stringent control on the carbon release, laws to facilitate the deployment of non-conventional and disruptive solutions at gigatons scale, public investments within a well-structure agenda for cutting emissions, and unlock CO_2 infrastructures to support storage or utilization (Fajardy et al., 2019; Fuss et al., 2020; Harvey et al., 2023; Hickey et al., 2023; Jagu Schippers and Massol, 2022; Lee et al., 2021; Muri, 2018; Schenuit et al., 2021; Tamme and Beck, 2021). The debate should move beyond an academic dissemination on CO_2 removal, a broader alliance of research and policy communities, industry, and the public is needed. Thus, we need to traduce concepts and ideas into actions (Fuss et al., 2020; Shayegh et al., 2021). In the meanwhile, CDR research must produce clear enhancement to make deployment economically feasible and appealing otherwise policies are not sufficient to support the initial momentum (Fuss et al., 2020; Shayegh et al., 2021; John Young et al., 2023). IEA report listed countries where governments have increased climate ambition and aggressively pushed forward an agenda to pursue climate neutrality or net-zero emissions by mid-century. Among these, European Union, Norway, Iceland, and the UK have been pioneer (IEAGHG, 2021a). More recently United States, Canada, and Australia launched ambitious plans for a full decarbonization (Harvey et al., 2023). However, there are still a few countries really committed to reach carbon neutrality. Beside the policies and strategies to support CDR solutions, anonymous surveys from experts on DAC and CDR technologies highlight that policy makers should account for public engagement and acceptance (Shayegh et al., 2021; Sovacool et al., 2022). For instance, recent polls reported in Cox et al. (Cox et al., 2020) and Wolske et al. (Wolske et al., 2019) point out that the public opinion is still not fully aware of what CDR technologies are and why these are needed to contrast the climate change. Public opinion has concerns about the effect of these solutions and how these could benefit to the environment and coexist with human activities. This aspect is still underrated and represents a potential problem to politicians and an hurdle for the deployment of climate positive actions.

1.3. The impact of DAC deployment

Cutting GHG emissions and capturing CO_2 from several sources at once are compelling and DAC is a promising solution. However, there are still challenges that should be considered and analysed, and more research is needed. Firstly, the cost of the captured CO_2 is relatively high if compared to conventional carbon capture technology from flue gas (House et al., 2011; IEAGHG, 2021b; Strefler et al., 2021, 2018). The low CO_2 partial pressure in the air leads to large mass flows processing resulting in large volumes and high energy consumption. Thus, DAC requires both high investment (CapEx) and operational costs (OpEx). Secondly, DAC facilities are expected to have a larger land footprint than conventional chemical processes due to the large area needed for the air contactors (Beuttler et al., 2019; Keith et al., 2018; McQueen et al., 2021b; National Academies of Sciences and Medicine, 2019; Robert Socolow et al., 2011). Thirdly, even though a DAC plant, in theory, could be installed in any remote area, there are some limitations due to the CO_2 supply chain (i.e., transport and storage), renewable energy availability and cost, and environmental conditions that affect the operation of the DAC facility itself (Direct Air Capture 2022 *A key technology for net zero*, 2022; IEAGHG, 2021b; Terlouw et al., 2021). All these aspects have an impact on the local and national level. Considering the above, Norway appears as a good candidate to host and deploy DAC facilities.

1.4. The Norwegian context

In Norway, there is a large availability of green energy, natural gas (to cover thermal energy demand, with CCS), and constructible areas not already utilised by the process industry, commercial or residential activity, or agricultural land. The electrical energy mix in Norway has a very low carbon footprint: 88 % of the total production in 2021 came from hydropower, whereas wind power covered 9 %. The remaining demand was fulfilled with fossil fuels. In 2021, the estimated GHG emission associated with electricity production and delivery in Norway was 11–30 kg_{CO2e}/MWh ("Hvor kommer strømmen fra?," n.d.; "Live 24/7 CO_2 emissions of electricity consumption," n.d.). This value is negligible if compared with other countries and energy sources ("Development of CO2 emission intensity of electricity generation in selected countries, 2000–2020 – Charts – Data & Statistics," n.d.; "Global Energy Review," 2022; "Greenhouse gas emission intensity of electricity generation in Europe," n.d.).

Usually, Norway has a higher renewable energy production than consumption and the surplus is exported to neighbouring countries, either by cables over land or sub-sea. Over the last 30 years there have been only seven years with net imports. Low precipitation is the major reason for net import (refer to Supplementary Material) ("Hvor kommer strømmen fra?," n.d.; "Hvor mye strøm selger vi til utlandet?," n.d.; "Produksjon, import, eksport og forbruk av elektrisk kraft (GWh) 1950–2021. Statistikkbanken," 2023). Additionally, Norway could shorten the supply chain since there are some CO_2 storage reservoirs with large capacities. These considerations are confirmed by Sendi et al. (Sendi et al., 2022). In detail, Norway presents average values for productivity (i.e., the volume of captured CO_2), but relatively high electricity consumption. Under different scenarios for the electricity cost, Norway always shows competitive levelized costs for the captured CO_2 from air: 275–500 USD/t_{CO2} on a scale of 225–700 + USD/t_{CO2} (Sendi et al., 2022). 275 USD/t_{CO2} is the lowest cost of the captured CO_2 in Norway when electrical energy is free, 0 USD/MWh_{el}, an unrealistic scenario, while 500 USD/t_{CO2} is the highest cost for the captured CO_2 in Norway when the electricity price was set to 100 USD/MWh_{el}. 225 and 700 + USD/t_{CO2} are boundary values corresponding to the cheapest and the most expensive CO_2 costs worldwide associated with negligible and most expensive costs of electricity scenarios, respectively. The electricity price in Norway has shown a larger variation than previously in the last 3 years (from 2020 to 3rd quarter, Q3, of 2022) as shown in the Supplementary material (Fig. S1) ("Elektrisitetspriser," 2023).

We assume that DAC facilities will pay the same as the energy-intensive process industry. Norway is divided into five electricity spot price areas. The spot price is based on auctions. In general, the price is lower in the two northernmost regions. The energy-intensive process industry normally has long-term contracts with producers. Some companies have a hybrid with some long-term contracts and some contracts linked to spot prices. This reflects a very heterogenous and fragmented scenario for the energy market and price in Norway. This topic has never been accounted for in the prior literature. The electricity prices for the energy-intensive process industry were 28.4 and 37.8 USD/MWh_{el} in 2020 and 2021 (using exchange rate 10 NOK = 1.0 USD), respectively, with a net increment of close to + 33 % in one year. In Q3 2022, the price raised to 50.2 USD/MWh_{el} with a further increase of at least + 33 %. The increment in 2022 (especially in Q2 and Q3) is also reflecting the recent geopolitical context: the shortage of energy due to the European Union's decarbonization strategy (including electrification) and the Russian aggression and invasion of Ukraine which further sharpen the demand for energy and energy vectors. In less than 3 years the prices for energy-intensive industry in Norway has almost doubled. The reported prices refer to a national average, but, as mentioned in the previously, in Norway the electricity price is region-based. Cheaper electricity is generally available in the north while the electricity is more expensive in the south. The Trondelag area (central region) experiences average conditions. The fluctuations in the electricity price suggests that national and even local "dynamics" should be included in the DAC deployment analysis. This will be commented on in the results and discussion section.

1.5. Novelty in the present work

Connecting back to Sendi's analysis, the most expensive scenario, 100 USD/MWh_{el} electricity cost, is more representative of the current situation (and future trend, as depicted in Fig. S1 in the Supplementary Material) for the electricity market price in Norway, thus, the cost per captured CO_2 expected to be approximately 450–500 USD/t_{CO2}. This assessment is quite encouraging because, even assuming the highest cost for electricity, Norway outperforms and it has one of the lowest costs per ton of captured CO_2 worldwide, using adsorption DAC technology. Despite Norway representing a country with relatively low total emissions and low carbon intensity of electricity, it is important to understand what it will take to do even more towards net-zero emissions. Prior analysis completely neglects any impact of DAC deployment on a national level. In other words, recent works by Sendi et al. (Sendi et al., 2022) and Izikowitz et al. (Izikowitz et al., 2023) are not considering if the DAC implementation is affordable for a country in terms of natural (land use) and energy (electricity and natural gas if available) resources. Their assessments are useful to point out potential limitations and aspect to be considered when dealing with DAC deployment. At best, they account for general indicators avoiding any detailed analysis of specific regional or otherwise local context such as policies and situations occurring in a specified country. This could be unfair because the proposed approaches disregard relevant elements and national dynamics affecting the sustainability of DAC as CDR technology. There are no works showing if the DAC deployment is affordable also accounting for local and national decisions. Prior literature addressed only the question on the energy consumption without any emphasis on the impact on the national energy plan and how the energy demand for DAC deployment may impact on the gross domestic product (GDP). As the world is moving to an uncertain climate future, considering technological means (there are many options and we focused on DAC) as a climate solution is important, but we need to consider all possible aspects, not only the positive effects. Despite Norway representing a country with relatively low total emissions and low carbon intensity of electricity, it is important to understand what it will take to do even more towards net-zero emissions. This article aims to present a preliminary assessment of the deployment of DAC facilities in Norway reflecting these missing elements. Though, we are not going to differentiate the cost of DAC according to the five electricity spot price areas. Our intent is to show that levelized cost and energy price are not the only parameters affecting DAC deployment. There are other factors that techno-economic assessments have not accounted for such as national energy strategies and markets, and potential natural limitations and barriers. These additional factors might lower Norway's current interest as a DAC hub. Still, decarbonization and carbon removal strategies are deeply interconnected with policy and energy plans, and these vary according to nation.

2. Materials and methods

For comparability with previous articles and analysis, we considered capturing 15 Mt_{CO2}/y, approximately one-third of the annual anthropogenic Norwegian CO_2 emissions, by focusing on land allocation and energy consumption and how the energy demand can be satisfied. The captured amount of CO_2 emissions is not randomly chosen. We started with a recent publication by Sendi et al. (Sendi et al., 2022) where the authors evaluated the costs of the DAC when contributing to remove 10 Gt_{CO2}/y by 2050. 10 Gt_{CO2}/y corresponds to 30 % of the global emissions of the global anthropogenic emissions in 2022 (36.8 Gt_{CO2}/y). The EU Parliament Bulletin on Climate Change Mitigation reports that the EU Commission endorsed more aggressive climate mitigation actions than the UN report (Gregor Erbach, 2021). Europe targets to reduce the emissions from the currently planned 40 % to at least 50 % in 2030. Net-zero emission is the environmental mission for 2050. In the last 5 years the Norwegian anthropogenic emissions oscillated around 42–45 Mt_{CO2}/y (European Commission. Joint Research Centre., 2022). We accounted for a scenario between the UN plan and the EU Parliament ambition; thus, accounting for a realistic target: a 33 % emission cut is an average. The UN report on global emissions suggests that the use of CDR technology to catch up the environmental commitments is probably underestimated, and the emissions cut could be more drastic by unprecedented levels ("Emissions Gap Report 2022," 2022). The same concept is remarked in Powis et al., where the authors point out a slow and insufficient deployment of CDR solutions to match the environmental targets proposed by international agencies and political entities (Powis et al., 2023). Similarly, Sun et al. showed through scenarios analysis that at the current rate of deployment of CDR technology, we will fail in cutting the emissions to the atmosphere and its analysis show that the carbon mitigation should be larger than planned (Sun et al., 2021). So, a 33 % capture of the yearly emission could be more realistic target. As still stated in the UN report, all countries are expected to equally contribute to cut the emissions and we assumed that each country contributes to the same measure. Hence, under this assumption, we assumed that Norway is expected to drop its emissions by one-third by 2050 even though it is one of the "greenest" countries in Europe and in the world. To pursue this scope of an unbiased analysis, we used suggested values provided in the most relevant reports by independent institutes (IEA, IEAGHG, and NASEM) and recent peer-reviewed publications (Table 1).

Before using any values, we crosschecked the references to verify how reliable these were. According to this approach, the range of values suggested by Sendi et al. for adsorption-DAC was compared to IEA and NASEM's suggestions showing a good agreement. Unfortunately, there are no "independent" estimates like Sendi's paper for solvent-based DAC. Keith et al. published a work on solvent-based DAC technology, but the authors are co-founders of Carbon Engineering. Thus, the NAMES report has been used as a reference for solvent-based DAC technology to validate and check values suggested by Keith et al. The estimates suggested by Keith et al. are aligned with the ones we find in

Table 1
References and material considered for the estimates.

Source and reference	Type of reference	Information	Note/comments
IEA (Direct Air Capture 2022 *A key technology for net zero*, 2022) IEAGHG (IEAGHG, 2021b)	Report	Land allocation Energy consumption Water loss/ consumption Land allocation Energy consumption Water loss/ consumption	The energy consumption (1.37–2.0 MWh_{el}/t_{CO2}) has been used to make a qualitative validation of values reported by Sendi et al. (1.45–2.56 MWh_{el}/t_{CO2}). IEA and IEGHG's estimated costs are not location-dependent (location and external conditions are not declared). IEA's reports provide only overall energy consumption to capture CO_2 and the corresponding share as thermal heat consumption. To make a direct comparison between IEA and Sendi et al. results, for the solid-DAC we considered 75 % of the share as heat consumption and a coefficient of performance (COP) for the heat pump of 2.5 to convert the thermal heat in electrical energy (IEAGHG). Sendi et al. included also the CO_2 compression to 150 bar. IEAGHG's techno-economic results suggest increasing by roughly 25–30 % of their estimates to account for this additional energy penalty not considered in their estimates.
NASEM (National Academies of Sciences and Medicine, 2019)	Book chapter	Information on the energy consumption for solvent-based DAC facility	The report suggests values for the alkaline electrolysers for H_2 production in substitution to natural gas combustion.
Sendi et al. (Sendi et al., 2022)	Article	Electrical energy consumption for adsorption-DAC considering the effect of the external environment conditions	Sendi et al. suggest 1.45–2.56 MWh_{el}/t_{CO2}. The wide range considers the DAC location. It is reasonable to consider an average value for Norway by looking at the results. The average value (2 MWh_{el}/t_{CO2}) corresponds to the upper limits in IEA and IEAGHG's reports. We adopted the wide range in Sendi's work to consider all possible values by also keeping in mind the warning on uncertainties asserted in IEA and IEAGHG's reports (conservative assumption). The range provided in this paper is aligned with the values suggested in IEA, IEAGHG (refer to the previous row of the table), and other previous publications such as Kiani et al. (Kiani et al., 2020) and Chauvy et al. (Chauvy and Dubois, 2022)
Keith et al. (Keith et al., 2018)	Article	Mass and energy balance for a large scale of Carbon Engineering technology	This work presents the simulation of the Carbon Engineering process using experimental data for model validation. The process flowsheet and corresponding balances have been used for the estimate of the energy consumption under the three investigated scenarios.

the NAMES report.

We considered only ad- and ab-sorption-based technologies as the alternatives, such as electro-swing adsorption, are still in their infancy. Therefore, their cost estimates are subjected to larger uncertainties. Moreover, electro-swing adsorption is more recent and has not been tested on a small pilot scale yet.

There are different options to supply heat and electricity to a solvent-based DAC process. We provide the estimates under three different scenarios: all-electric, natural gas-based, and hybrid. In the all- electric scenario, we assumed that the thermal energy demand is covered by burning hydrogen produced through electrolysis which consumes electricity from the national grid. The presence of hydrogen production entails an extra increase in the electrical energy demand. In the so-called natural gas-based scenario, the DAC plant relies exclusively on natural gas, thus, a gas turbine satisfies the electrical demand, and the combustion of the natural gas provides the thermal heat in the calciner. In other words, both electrical and thermal requests are fulfilled through natural gas combustion with CCS. Finally, the hybrid case considers an intermediate condition where the national electricity grid covers the electrical energy demand, while the combustion of natural gas still compensates for the thermal supply. For both hydrogen and natural gas combustion, we considered low heating value (LHV) for the combustion heat for the sake of conservatism. Both reports and articles include inefficiencies distributed all around the process in their estimates, so we did not have to add additional margins of safety to avoid over-optimistic estimates.

We consider only all-electric for the adsorption-based DAC. We disregarded any hybrid scenario (i.e., natural gas combustion for covering the thermal demand) because Climeworks is going to test in Iceland (Orca and Mammoth plants) solutions with integrated heat pumps to recover waste heat for the adsorbent regeneration. This technical solution is also the only one considered by Sendi et al. (Sendi et al., 2022).

We also decided to make a comparison between the national electricity production and natural gas production. To make an unbiased, but up to date and reliable, analysis, we referred to the Norwegian natural gas export of 2021 as we view the 2022 increase in natural gas production and export a result of extraordinary geopolitical factors. Norwegian natural gas export and production increased in 2022 due to unstable supply from Russia. Russia has been one of the largest suppliers of natural gas to Europe. In June 2022, Russia cut the natural gas flow by more than half. It both stopped and resumed in July, and then in September 2022, it stopped altogether. Norway compensated for the reduction in Russian supply by increasing its production and export. For the same reasons, we referred the electrical energy production to 2021. It is remarkable that the electricity price was rising also in 2021 (Fig. S1 in Supplementary Material) and the rising trend was already established in 2019. 2020 should be neglected due to the pandemics: the lower energy demand due to partial stop in the energy-intensive process industry during the lock down caused a significant drop in the price of electricity.

We further performed a second analysis of the adopted values for the electricity and thermal energy consumption to get a more rigorous and careful check. We reviewed the prior literature as suggested in Chauvy et al. (Chauvy and Dubois, 2022) (results in Fig. 1) for Climeworks (solid adsorption) and Carbon Engineering (liquid solvent). These are the two technologies investigated in our paper. The average or central value (yellow), the average of the maximum/upper limits (green), and the average of the minimum values/bottom boundary (red) are highlighted with the coloured horizontal lines. We calculated the average values for solid- and liquid-DAC separately. For this estimate, the IEA report values have not been included in the calculation as we wanted to use IEA's estimate as a reference indicator to better visualize how peer-reviewed literature could be far from or close to international agencies' estimates. Grey-shaded areas represent the overall average (central value and confidence interval calculated on the base of average values of the maximum and minimum peaks) disregarding the technology. This additional analysis is not a complete and exhaustive review of the entire literature on the topic because it would be out of scope. However, it provided us with the confidence that the adopted values are accurate enough for the preliminary assessment we would carry out.

Despite the large uncertainties, such as "error" bars in the chart, several estimates from prior literature share a quite uniform and homogenous assessment of the energy input for DAC facilities regardless of the technology. Indeed, the central values (yellow lines) of both liquid- (Carbon Engineering) and solid-DAC (Climeworks) for both electrical and thermal energy fall into the grey area. This is not surprising because it is compliant with the thermodynamic assessment provided by House et al. (House et al., 2011). In their work, House et al. estimated the minimum thermodynamic work required to sequester and concentrate the captured CO_2 from the air disregarding the technology chosen to

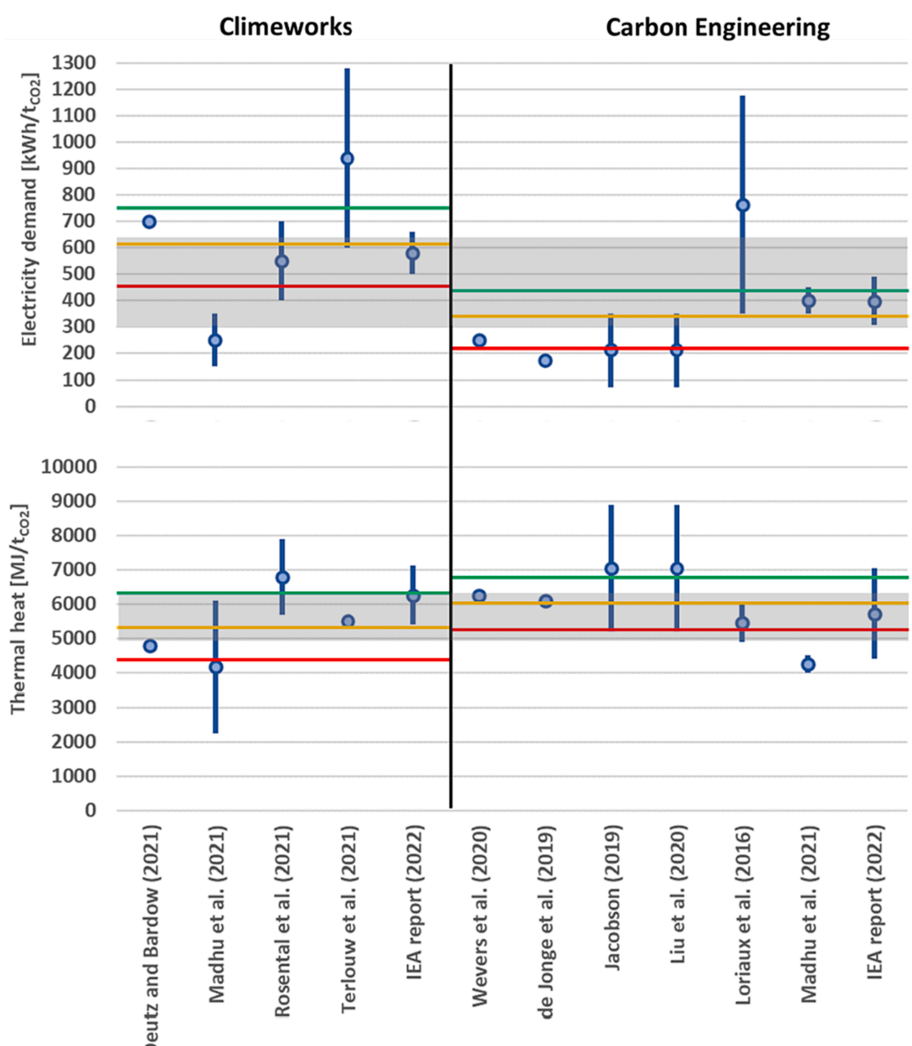

Fig. 1. Overview of the literature estimates for DAC energy consumption electricity (A) and thermal (B). The estimates are clustered according to the technology: Climeworks (solid adsorption) and Carbon Engineering (liquid solvent). The average value, average of the maximum (upper limits), and average of the minimum values (bottom limits) are highlighted the yellow, red, and green horizontal lines, respectively technology-by-technology. Grey-shaded areas represent the overall average (central value and confidence interval) disregarding the technology. References: Deutz and Bardow (Deutz and Bardow, 2021), Madhu et al. (Madhu et al., 2021), Rosenthal et al. (Rosental et al., 2020), Terlouw et al. (Terlouw et al., 2021), IEA report (Direct Air Capture 2022 *A key technology for net zero*, 2022), Wevers et al. (Wevers et al., 2020), de Jonge et al. (de Jonge et al., 2019), Jacobson (Jacobson, 2019), Liu et al. (Liu et al., 2020), Loriaux et al. (Loriaux et al., n.d.).

perform the separation of CO_2 from the air. They demonstrated that the expected actual energy input is far larger, at least twenty times the corresponding minimum work, even though the calculated minimum work for DAC is only five times the calculated actual work for CO_2 capture from flue gas (CO_2 concentration 5–12 % v/v) using conventional solvent-based technology.

3. Results and comments

Table 2 gathers our estimates for the total capture of 15 Mt_{CO2}/y for both solid-based and liquid-DAC technologies in the Norwegian context. Currently, the possibility to install DAC plants close to the energy farm is a strategic option and the DAC facility consumes the energy surplus. There is also interest in small modular reactors where nuclear power supply heat and power to solid-based DAC to fully cover the electrical and thermal energy demand (Erans et al., 2022; Lackner and Azarabadi, 2021; McQueen et al., 2021a, 2021b; Slesinski and Litzelman, 2021). These options require quite large areas because the DAC is planned close to energy facility. In Norway there is plenty availability of land. Land allocation may not represent an issue, but there are still some location-dependent pending issues. The Norwegian terrain is rugged and mountainous, and this could represent a natural barrier for the solvent technology that is planned to be built for large-scale "compact" plants. Compact means that the series of operations (capture, slacker, calciner, and other units) are expected to be close to one another, thus these should be installed in an almost flat area (Holmes and Keith, 2012; Keith et al., 2018). Conversely, the adsorption-based DAC is more flexible since it is modular and designed in 7-meter-thick rows (Beuttler et al., 2019; Gebald et al., 2015). Further, it does not require that ancillary facilities are close to the capture unit since cyclic adsorption and desorption steps are performed within the same volume corresponding to the volume of the module. Regardless of the technology, the external environment is expected to influence DAC efficiency and performance. For this reason, the location is still an open question in Norway. Sendi et al. fixed the minimum operating temperature around −15 °C and for not more than fifteen consecutive days per year for the adsorption process. Unfortunately, there is not any similar work for the solvent-based DAC yet. However, it is reasonable to assume cold weather complicates solvent management (Leonzio et al., 2022; Leonzio Grazia et al., 2022). The minimum requirement claimed by Sendi et al. is met along parts of the coastal areas in Norway, but not in the inner countryside (https://www.met.no/en/weather-and-climate). Moreover, there is neither information nor technical reports about the impact of corrosion associated with seawater spray and aerosols and potential issues as icing may occur, as well. These are additional elements to be accounted for when deciding locations for cold and humid weather.

The energy analysis points out that the DAC facilities are substantially energy-starved plants, and these should consume the excess energy available in the national grid. The solid-based DAC is expected to consume 15–25 % of Norwegian electricity production. For this technology, we adopted the consumption range suggested by Sendi et al. for adsorption DAC. Such a broad range of energy consumption reflects (1) on one side the large uncertainties associated with estimates as also reported in IEA's reports and (2) on the other side, the impact of environmental conditions on the DAC performance. Even though estimates bring large uncertainties, the solid-DAC solution consumes a significant percentage of the national electricity production. Solvent-based DAC seems to be a less electricity-intensive process. The all-electric solvent DAC has the largest energy consumption which corresponds to 40 % of the national energy production. Alkaline electrolysers are responsible for the substantial increase in electricity demand (National Academies of Sciences and Medicine, 2019). These units absorb 94 % of the overall estimated energy demand.

The electricity consumption is to be compared not only with the energy availability but also with the energy excess (accessible and ready-to-use). In 2021, the net electricity energy surplus, the energy

Table 2
Results of the preliminary assessment for DAC deployment in Norway (captured volume: 15 Mt_{CO2}/y).

Technology (plant capacity)	How many plants?	Footprint (only DAC facility)	Electricity consumption	Thermal energy demand	Notes
Solid-based DAC (4 kt_{CO2}/y)	3750	22.5 km[2]	21.8 – 38.4 TWh_{el}/y (13.9 – 24.4 % of the Norwegian electricity production[1])	–	Based on the current maximum capacity of solid-DAC (Orca).
Solid-based DAC (36 kt_{CO2}/y)	417				Scale-up scenario (Mammoth plant under construction).
Liquid-based (1 Mt_{CO2}/y) Fully electric	15	6–8 km[2]	Baseline 3.75 TWh_{el}/y Electrolysis 59.13 TWh_{el}/y (62.88 TWh_{el}/y corresponds to 40 % of the Norwegian electricity production)	–	Overall electricity consumption is 62.88 TWh_{el}/y. The alkaline electrolyser provides the hydrogen to cover the thermal demand and reference values for 1.0 Mt_{CO2}/y scale are in the NASEM report. The land allocation does not account for the electrolysers soil footprint. The baseline case includes all the electricity demand for air fans, pumps, and any pieces of equipment different from the calciner.
Liquid-based (1 Mt_{CO2}/y) Natural gas-based			–	37.77 TWh_{th}/y (4050 million Sm^3 – 3.32 % of the natural gas export[2])	The DAC facilities will consume around 4050 million Sm^3 yearly of natural gas which corresponds to 3.32 % of the Norwegian natural gas export
Liquid-based (1 Mt_{CO2}/y) Hybrid			3.75 TWh_{el}/y (2.4 % of the Norwegian electricity production)	25.70 TWh_{th}/y (2755 million Sm^3 – 2.26 % of the natural	The natural gas consumption is around 2755 million Sm^3 which corresponds to 2.26 % of the

(continued on next page)

Table 2 (*continued*)

Technology (plant capacity)	How many plants?	Footprint (only DAC facility)	Electricity consumption	Thermal energy demand	Notes
				gas export)	Norwegian natural gas export

[1] Reference value 157.113 TWh in 2021 – source Electricity (ssb.no).
[2] Reference value 122 billion of Sm^3 of natural gas export in 2021 – source Exports of Norwegian oil and gas - Norwegianpetroleum.no (norskpetroleum.no).

produced, but not consumed and exported from Norway to neighbouring countries) was around 15 TWh (almost 10 % of the annual production), but this value is expected to reduce to 3 TWh, which is less than 2 %, by 2026 ("Increased power consumption and plans for new industry generates need for more power production," 2023). The drop in the energy surplus is mainly driven by increased electricity consumption in transportation, hard-to-abate, and power-intensive industries, and the oil and gas sector electrification. The reduction in excess electrical energy is forecast even if power generation plants are planned. Currently, this implies that many of the proposed scenarios for DAC are not fully implementable in the Norwegian context due to a lack of resources to make them nationally self-sustainable. Moreover, all the proposed scenarios will become less and less appealing and feasible in the coming years due the decreasing availability of energy surplus to be used for DAC implementation. Furthermore, natural gas consumption is an additional concern. The extra demand for natural gas to be supplied to the DAC facilities ranges from 2.3 to 3.3 % of the Norwegian natural gas export in 2021. This corresponds to 2755 and 4050 million standard cubic meters of natural gas per year, respectively. The export of up to 3.3 % of the 2021 natural gas production would impact the national Gross Domestic Product (GDP), thus, the Norwegian energy and economic strategies. According to the Statistisk Sentralbyrå (Statistics Norway), in 2022, the GDP of Norway was 5,793 billion NOK ("Norwegian economy in 2022," 2023; "Skyhøye gasspriser ga historisk høy eksport i 2022," 2023). To convert in USD, consider an exchange rate of 10 NOK per 1.0 USD. The revenues from the natural gas trades were 1,457 billion NOK ("Skyhøye gasspriser ga historisk høy eksport i 2022," 2023; "The government's revenues," 2022). Hence, natural gas export covered 25.2 % of the national GDP. The natural consumption to satisfy the thermal energy demand for DAC facilities will correspond to ~ 1 % of the GDP of Norway (i.e., 5.73 billion NOK). In 2021, the revenues from natural gas were 573 billion NOK and the GDP was around 4,900 billion NOK. Natural gas covered 12.7 % of the GDP. The natural consumption to satisfy the thermal energy demand for DAC facilities corresponds to ~ 0.5 % of the GDP of Norway (i.e., 2.45 billion NOK). The fraction of the GDP to be allocated ranges from 0.5 to 1 % of the GDP, but if the increasing trend for natural gas is expected to stable, it is likely that the impact of the DAC on the GDP will become more and more significant. The present discussion is limited to the natural gas consumption. The analysis should also account for electricity production and distribution because solid-DAC is planned to be fully electricity-driven and liquid-DAC may consume electricity from the national grid for gas compression and liquid circulation. Our preliminary assessment showed that there is a lack of energy to make the DAC facilities fully operative without any electricity trade with country selling their energy surplus. The impact of the construction of new energy power stations (natural gas-fired power stations, renewable energy farms, and so forth) on the GDP of a country is uncertain, but this contributes to increase in the weight of energy consumption of DAC on the GDP. For instance, IEA estimated that energy-related expenditure accounted for 4.8 % Unites States GDP in 2020 ("2020 inflation-adjusted U.S. energy expenditures lowest since 2002," 2023). This was the lowest value ever registered. The report *Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use* by NASEM (Council, 2010) in 2010 showed that energy production, maintenance of the infrastructure, and distribution have a substantial impact on the GDP, a few percentage (2–3 %), but there are also hidden costs negatively impacting on the GDP such as indirect GHG and harmful compounds emissions. As a matter of fact, the electricity production and distribution for DAC is expected to have an impact on the GDP of Norway, even if it is not possible to quantify it with the available information. Albeit with some national variations, the DAC deployment will weight for few percentage points on the GDP and this element should be also considered.

This aspect reflects that DAC deployment is not a merely technical problem, but it involves other branches such as the economy (i.e., billions of financial resources) and social and political science (policies, strategies, decision making, public opinion and engagement). This aspect has already arisen in other papers and similar considerations can be applied to any other country worldwide.

Reports also point out additional features to be accounted for when considering natural resource consumption in DAC technologies. Among these, water consumption deserves a few comments even if Norway has a relative abundance of hydropower reservoirs. Once again, the estimates are affected by large uncertainties, but reports are almost aligned on average. DAC water consumption is strongly correlated to humidity and environmental conditions. As a general trend, solvent-based DAC is subject to water loss mainly concentrated in the absorption system due to solvent evaporation. Other sources of loss are the slaker and the calciner units (Keith et al., 2018). The water loss could be negligible but on average NASEM (National Academies of Sciences and Medicine, 2019) suggests considering 8.2 t_{H2O}/t_{CO2} of water make-up to offset the losses during the year. NASEM value has been calculated based on experimental data from caustic solvents like the one used in the Carbon Engineering process. IEAGHG reports (IEAGHG, 2021a) an even worse scenario: the water make-up could be up to five times larger. The loss of water could be a barrier for solvent-based DAC deployment in non-arable locations, like deserts, or in areas where the CO_2 capture using this technology contrast with other activities such as agriculture and/or biomass growth and harvesting for other industrial activities, for example bioenergy generation. For 15 Mt_{CO2}/y global capture volume, the make-up of water is almost 123 million cubic meters per year. That is 3.9 tons/h of water). Instead, adsorption-based DAC generally releases water into the environment (Direct Air Capture 2022 *A key technology for net zero*, 2022; IEAGHG, 2021a; Wurzbacher et al., 2016). The humidity is cyclically adsorbed and desorbed within the porous materials and the entrapped or captured humidity entails net water production. The condensed water released from solid-DAC can be also negligible when the sorbent is designed for sharp selectivity to the CO_2 (J. Young et al., 2023), but reports suggest considering on average from 1.5 to 2 t_{H2O}/t_{CO2} released to the environment. For this reason, the adsorption-based process can be also implemented in arid areas.

4. Conclusions

This article briefly investigated the role and the impact of the location and the corresponding national dynamics on DAC deployment. Norway is a good candidate for hosting DAC facilities due to the availability of land, renewables, and low carbon-footprint electricity surplus, currently exported, as well as natural gas to satisfy the thermal energy demand and geological reservoirs to minimize the cost of transportation and storage of captured CO_2. Although Norway fits many requirements, there are still some concerns.

The analysis focused on capturing one-third of the annual emissions in Norway, 15 Mt_{CO2}/y. It shows that the location of DAC facilities is an open question since there are environmental conditions to fulfil to properly run the DAC plants. Temperature and humidity affect performance. Further, energy consumption penalizes DAC deployment. The electricity demand would be 14–25 % of the Norwegian annual production of electricity for the adsorption process, but it is limited to 2.4 %

in the hybrid case study for the solvent-based DAC. This value rises up to 40 % for an all-electric solvent-DAC process. Nevertheless, solvent-based DAC is going to consume from 2.3 to 3.3 % of the Norwegian export of natural gas (reference 2021). This implies that from 2755 to 4050 million standard cubic meters of natural gas are consumed, and not exported, to address the internal energy demand for all the DAC facilities.

The DAC energy demand to capture one-third of the Norwegian emissions could conflict with the electrification plan for the transport sector, the hard-to-abate industries and the oil and gas sector. This energy strategy will further reduce the Norwegian electricity surplus from 15 TWh in 2021 to 3 TWh in 2026. The decrease in the surplus will reduce the possibility of sustaining the internal energy demand for DAC facilities using the national electricity grid. If Norway would install and operate an all-electric driven fleet of DAC facilities, the national energy production should grow correspondingly, from 14 to 40 % depending on the scenario, and at the same time.

This example shows that the DAC deployment is a "nation" dependent process even if models and indicators would suggest Norway as an ideal candidate to test and validate DAC technologies. DAC construction involves elements beyond the technical discussion such as national energy strategies and policies, which are out of the scope of our dissemination. Our analysis focused on the possible technical barriers to the DAC deployment in Norway based on international reports and recent publications, but we would remark that also international institutes claim their estimates may suffer from uncertainties since DAC has not been already implemented and deployed on an industrial scale.

We hope that this short communication has pointed out that any DAC analysis cannot disregard considerations for the national context in terms of potential and energy availability for the DAC installation and operation.

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

No data was used for the research described in the article.

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Appendix A. Supplementary data

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