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What is the potential of bioCCS to deliver negative emissions in Norway? From biomass mapping to a window of negative emissions potential

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ABSTRACT

Negative emissions have been highlighted as a key component of achieving the net-zero ambition. However, ground-up approaches are necessary to better understand the realistic potential of negative emissions technologies at the national or continental level. Such an approach was applied in the present study to understand the potential of bioenergy with carbon capture and storage to deliver negative emissions in Norway, starting from mapping and quantification of biomass until the derivation of a window of negative emission potential.

The results indicate that bioenergy with carbon capture and storage could enable between 1 and 13 $MtCO_2/y$ of negative emissions, with a more probable range between 2 and 8 $MtCO_2/y$, at least in the coming decades. These values are drastically higher than the potential identified in previous studies, thus highlighting the importance of bottom-up approaches, like the one adopted here, to better estimate the negative emissions potential that could be delivered by bioenergy with carbon capture and storage.

In terms of biomass, the strongest potential for negative emissions comes from the integration of forestry resources and activities with bioenergy with carbon capture and storage. However, it is important to ensure that this integration takes place in a sustainable way and does not result in a decrease in the standing volume of the Norwegian forest for multiple reasons. Integrating waste with bioenergy with carbon capture and storage also represents a significant potential to enable negative emissions, especially as a substantial fraction of waste is already integrated with energy production. Finally, biomasses from agriculture and seaweed farming are expected to have a limited potential to enable negative emissions, although seaweed farming could take a more significant role towards the second half of the century, depending on the development of this sector.

1. Introduction

1.1. Why negative emissions?

Anthropogenic emissions of greenhouse gases since the first industrial revolution have been shown to increase the global average temperature [1]. While this temperature increase is “only” a few degrees, global warming is already leading to dire consequences, which will further accentuate if the rise in greenhouse gas emissions to the atmosphere is not limited [2]. While many technologies are expected to contribute to the fight against climate change, negative emissions technologies (NET) are now seen as a critical component of achieving the net-zero by 2050 ambitions [2]. Indeed, such strategies have been consistently highlighted as central to compensate for hard-to-avoid emissions, as well as to reduce a possible overshoot in our remaining carbon budget to meet the 1.5 °C target considering the current slow trajectory in reducing emissions [3].

NETs are technologies that remove greenhouse gas emissions from the atmosphere and ensure that they are permanently prevented from being released back into this atmosphere. There are, in practice, six main negative emissions pathways: 1) afforestation and reforestation, 2) biochar and soil sequestration, 3) ocean fertilization, 4) bioenergy (e.g., heat, power, hydrogen) with carbon capture and storage (CCS), 5) enhanced weathering, 6) direct air capture (DAC). Amongst these, bioenergy with CCS (bioCCS) has been consistently highlighted by the Intergovernmental Panel on Climate Change (IPCC) as a key strategy to

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Abbreviations: BECCS or bioCCS, Bioenergy with carbon capture and storage; CCS, Carbon capture and storage; CDR, Carbon Dioxide Removal; d.b., Dry basis; DAC, Direct air capture; IPCC, Intergovernmental Panel on Climate Change; NET, Negative emissions technologies.

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enable the negative emissions levels to reach net-zero [2]. According to the International Energy Agency's (IEA) net-zero by 2050 roadmap, 1375 million tonnes of CO_2 per year are expected to be captured from biogenic sources by 2050 [4].

1.2. What is bioCCS?

Plants absorb CO_2 from the atmosphere through photosynthesis and use this CO_2 for their growth as part of the "carbon cycle". The combustion of biomass (or biofeedstock), such as wood, is ideally considered to result in no additional anthropogenic emissions of CO_2 to the atmosphere as the CO_2 absorbed through photosynthesis is simply returning to the atmosphere.

When the CO_2 resulting from this combustion is captured and permanently prevented from returning to the atmosphere, this process, called bioenergy with CCS (bioCCS or BECCS), results in negative emissions, as CO_2 is effectively taken out of the atmosphere and permanently prevented from returning. This process is illustrated in Fig. 1. The biomass used in such a process can come from different sources, such as agricultural by-products, household waste, forestry residues, etc.

It is worth noting that bioCCS is, in practice, not limited to the capture and storage of CO_2 resulting from biomass combustion but more generally of CO_2 whose carbon is from a biogenic origin. This thus includes, for example, CO_2 resulting from the conversion of biofeedstocks to low-carbon energy carriers, such as hydrogen, as well as biocarbon-based feedstock for use in industry such as CO_2 produced by the use of biocarbon-based electrodes. Hence, while the BECCS and bioCCS terms both correspond to bioenergy production with CCS, the term bioCCS generalizes the umbrella covered by BECCS, which is commonly used to reflect only production of heat and/or power. In addition, while the term BECCS often refers to facilities producing low-carbon footprint heat and/or power for external facilities or end-users, bioCCS also includes pathways where bioenergy is produced and used within given industrial facility.

Finally, to be considered a negative emission technology, it must also fulfill the additional criteria set by Tanzer and Ramirez [5,6]. This requires that all the greenhouse gas emissions along the bioCCS value chains must be accounted for in order to quantify if and how much net negative CO_2 emissions are effectively enabled.

Amongst the aforementioned negative emission pathways, it should be noted that bioenergy enables other economic and climate advantages in addition to negative emissions. BioCCS is a net energy-producing technology. This essential characteristic means that bioCCS enables significant revenue streams, does not add further stress on the current energy systems, and can help reducing reliance on fossil sources and their associated anthropogenic CO_2 emissions.

1.3. Goal of the study

To enable widespread deployment of bioCCS-based negative emissions solutions, the Carbon Dioxide Removal (CDR) Mission Innovation has identified five top priority areas [7]:

1) The mapping and characterization of biomass feedstock resources;
2) The development of harmonized methodology for techno-economic and environmental assessment of bioCCS;
3) The development of bioCCS value chains proven to be net negative and in which the carbon is stored in a manner intended to be permanent;
4) The reduction of costs of bioCCS through research and development;
5) Pave the way for building pilot and demonstration bioCCS facilities.

The present study focuses on the first of these priorities, in the Norwegian context. In particular, the aim is to identify and quantify biofeedstock types, as well as the maximum and realistic potential level of negative emissions that could be derived from integrating these with bioCCS. Indeed, while many studies assumed that biomass is readily available, there is a limited understanding of how much and what types of biofeedstocks could be available for bioCCS. This step is crucial as it is necessary to understand the maximum and realistic levels of negative emissions that could be delivered, identify pathways for integrating these biofeedstocks with bioCCS, evaluate the techno-economic and environmental performances of these, understand advantages and challenges, etc.

While mapping biofeedstocks may appear to be an easy task, there are many challenges in doing so. For example, biomass is a diverse and heterogeneous resource, detailed quantitative and qualitative data are not always readily available, well-documented, nor uniform [8,9]. The production of some biofeedstocks has also evolved in the past decade [10,11], making some of the previous assessments obsolete. Furthermore, a good understanding of several aspects is required in order to assess the negative emission potential of bioCCS. These include carbon content, current uses, collection feasibility, transport and conversion, emissions associated with the bioCCS value chain, etc. [7].

The present paper is structured as follows. First, the approach adopted to identify and quantify biofeedstocks in Norway, as well as estimate the associated negative emission potential is presented. Secondly, the results of the biofeedstock mapping and assessment of the negative emissions potential of bioCCS in Norway are presented and discussed. Finally, conclusions and recommendations for future work are presented.

2. Methodology

The approach adopted to estimate the potential of bioCCS to deliver negative emissions in Norway comprises twofold. First, the current

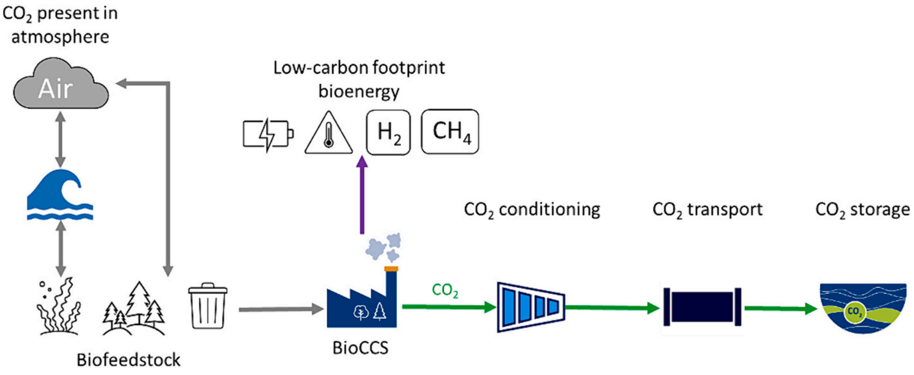

Fig. 1. Simplified illustration of the concept of bioCCS pathways.

situation of biomass produced in Norway based on year 2020 estimates must be established. Secondly, the outcome of this biomass mapping is used to estimate the theoretical maximum level of negative emissions, as well as a more realistic negative emissions window.

In order to establish the current situation of biomasses produced in Norway, the following steps are followed:

1. The type and quantity of biomasses currently (2020 being used as a baseline year) being produced in different applications (agriculture, forest, aquaculture, ocean, food waste, etc.), including residues, waste and by-products, are mapped. Fig. 2 illustrates the main types of Norwegian biomasses and how they are categorized between agricultural residues, forestry biomass, marine biomass, and waste biomass within the present study. It is worth noting that non-utilized residues, by-products, and both imported and exported biomass are also included. Living animals and plants used to produce food are not included, but the associated residues and wastes are. Peats are also excluded because they are not considered to be sustainable/renewable.
2. Considering the carbon weight fraction derived from the chemical composition of each of these biofeedstocks, the associated amount of CO_2 that has been absorbed from the atmosphere via photosynthesis is estimated.
3. Finally, how much of this CO_2 could be permanently stored via the integration of these biomasses with bioCCS is estimated. In order to do so, it is critical to characterize how each biofeedstocks is currently being used so that integration with bioCCS does not result in radical change in current types of use. Current uses of these different biomasses can include energy applications (heat and power), energy carriers (e.g., biogas, methane), materials (paper, building materials), soil improvement, organic fertilizer, etc. While many biomass- and case-specific aspects can lead to considering how much of a biofeedstock can be integrated with bioCCS, this study adopts the following overall principles:

- Biofeedstock quantities that are currently used in energy applications and energy carriers' production are considered to be compatible with bioCCS;
- Biofeedstock quantities converted to non-energy products (e.g., paper, building materials, feed) are not deemed compatible with bioCCS without significantly disrupting existing markets;

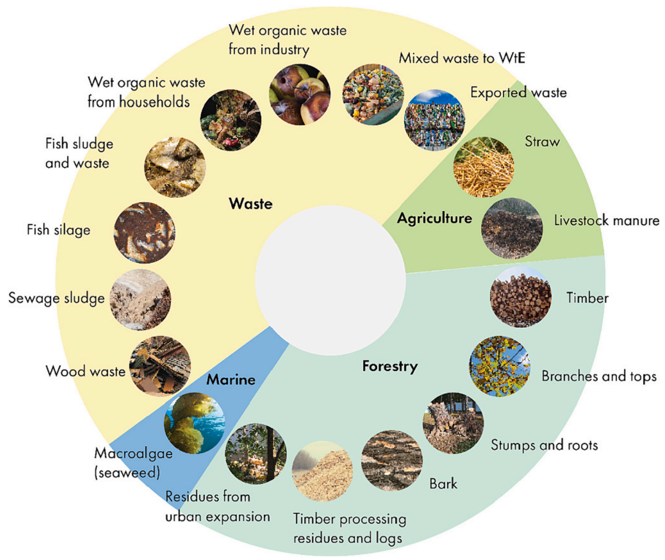

Fig. 2. Types of biomasses identified and how they are categorized between agriculture, forestry, marine, and waste.

- Other biomass quantities that could technically be used for bioenergy production but are currently unutilized or utilized in a way deemed sub-optimal (see Supplementary Information for case-to-case discussions), are also deemed compatible with bioCCS if they seem sustainable and ecologically sound. For example, fractions of agricultural wastes can be used for soil improvement, however, excess quantities could be integrated with bioCCS. Similarly, exported waste could be treated in Norway in bioCCS applications.

Finally, while the supplementary information presents more detailed information on the above steps per biomass type, including reflections and references used, it is important to note that two main types of sources have been used as part of this first step: official statistical data from Statistics Norway and sector-wise reports from consultants/research institutes/academia (usually in Norwegian). While some sectors have been collecting detailed data for decades and have well-established, robust methods (e.g., the forest sector), other sectors are newer or fragmented, and collecting accurate numbers can be more challenging. However, overall, the authors believe the available numbers provide a representative picture of the current situation.

In the second fold, the obtained characterization of the current situation of biomasses produced in Norway is used to estimate the theoretical maximum level of negative emissions that could be delivered by bioCCS, as well as a more realistic negative emissions window following the steps presented below:

1. Considering that it would take a few years to deploy bioCCS in Norway at a large scale, the bioresources situation established for 2020 is used to elaborate scenarios that aim to illustrate how this situation might evolve towards 2030.[1] These scenarios aim to capture how current quantities of biomass produced could evolve at the national level, the potential of new or not-currently-valorized biofeedstocks, and the implication for integration with bioCCS. Based on these, the theoretical maximum amount of negative emissions that could be delivered by bioCCS in Norway is drawn. The three scenarios considered are summarized below:
   - "Business-as-usual" scenario: where the result obtained for the 2020 situation are updated to represent the 2030 situation assuming annual increase/decrease in quantities using historical statistical data and considering an unchanged state-of-play concerning biomass uses and the fractions that are possible to integrate with bioCCS;
   - "Expansion" scenario: which, in addition to the "business as usual" scenario, includes that three main events take place 1) the forest is harvested to its balance quantum (i.e., all growth is taken out and goes to the same applications as today) [12], 2) seaweed production takes off according to currently forecasted estimates [13], 3) combustible waste fractions currently exported to Sweden are assumed to be treated (i.e. incinerated with energy recovery) in Norway [14];
   - "BioCCS-driven expansion" scenario: where the aforementioned events take place but are solely motivated by bioCCS, meaning that, for example, all the additional biomass from the quantum harvesting of the forest is integrated with bioCCS.

2. While the above step provides a good ballpark figure of the maximum theoretical potential bioCCS to deliver negative emissions in Norway, it is highly unlikely that this maximum potential would

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[1] The 2030 was here adopted to account for time required to deployed such value chain, and because the strong EU emission reduction target (at least 55% compared to 1990 levels) of this phase gate may required a significant level of negative emissions to be met. Finally, while longer time perspectives are likely more relevant for the realization of high level of negative emissions, it also comes with great level of uncertainties.

be achieved for various reasons (competition for biomass, lack of economic incentive and suitable policies, logistic challenges, conversion limitations, etc.). To better understand the levels of negative emissions which could realistically be delivered, two overall categories of factors impacting the level of negative emissions delivered are considered:

- Level of access to biogenic carbon: while the theoretical maximum amount of biomass, and hence biogenic carbon, that could be integrated with bioCCS is obtained from the previous step, the amount effectively available could be lower due to, for example, competition for biomass, biodiversity considerations, social acceptance, etc.
- Level of negative emissions implementation: even for a set amount of biogenic carbon available, different levels of negative emissions could, in practice, be delivered by bioCCS. Indeed, in practice, several factors might impact the amount of negative emissions effectively deployed and delivered. These include economic incentives, policy framework, demand for bioCCS-resulting energy carriers, potential logistic and conversion challenges, greenhouse gas emissions associated with the bioCCS chain deployment and operation, etc.

As different pathways are possible within these two categories (access and implementation), the result of this final step is given in the form of a window of possible negative emissions levels that could be delivered by bioCCS in Norway.

3. Results and discussions

3.1. Current situation of biomasses produced in Norway

As discussed earlier, the first step in estimating the negative emission potential of bioCCS in Norway is to establish the current situation of biomass being produced. The following sections and Table 1 summarize the results of this mapping and characterization for the four bioresource categories: agricultural residues, forestry biomass, marine biomass, and waste biomass. Meanwhile, the supplementary information provides a more detailed description of the current situation, biomass properties, current utilization, and how the level of integrability was selected based on multiple factors (properties, regulations, current uses, ecological considerations, etc.).

3.1.1. Agricultural residues

Agricultural residues are of two origins: animal and vegetal. The raw amount of livestock manure is amongst the largest single biomass fraction (almost 10 million tons per year). However, due to its very high moisture content (above 80 wt%), a limited carbon content is present in this biomass. Livestock manure is currently mainly spread on fields as a soil enhancer. However, only limited quantities can be spread for both regulatory and logistical reasons, offering some opportunities for integration with bioCCS.

The main agricultural plant residue in Norway is straw from cereals harvesting. A large percentage of this straw is left in the field for soil enhancement as it is rich in nutrients (minerals, nitrogen, alkalis), resulting in a limited carbon potential for integration with bioCCS.

Overall, agricultural residues are deemed to offer a limited potential negative emission via bioCCS, although not negligible.

3.1.2. Forestry biomass

Given the current value chains and existing practices in Norway, forestry biomass (i.e., trees) can be categorized into four main fractions: 1) timber (to non-energy products, i.e. paper and materials), 2) residues from timber processing, including logs and bark, 3) branches and tops, and 4) stumps and roots.

Timber is the largest single fraction of forestry biomass in terms of total weight (with almost 10 million tons), as well as when it comes to total carbon weight. The timber market is complex, involving many actors, fractions, and applications. Most of the timber produced in Norway ends up in materials (building materials, pulp and paper, furniture) or is being exported. Meanwhile, the lower quality fraction, such as logs, are used in wood stoves, a widespread traditional source of residential heating in Norway. Different residues are generated during timber transformation processes: sawdust, shavings, chippings of various sizes, etc. These residues are currently valorized in various applications such as bioenergy production and often internally (e.g., for drying) in the wood processing industries.[2] Finally, a small fraction of the timber is used as a reducing agent in the Norwegian metallurgic industry. However, overall, timber is mainly employed in non-energy applications that cannot be integrated into bioCCS. Considering the current timber uses, only 24% of the produced quantity is here deemed integrable with bioCCS.

In addition to timber, branches and tops, which are currently left in the forest mainly for economic and ecological reasons, could be integrated with bioCCS to a large extent. Meanwhile, the stumps and roots are commonly left in the forest for ecological reasons and are thus not deemed reasonable to integrate with bioCCS.

Overall, several forestry-based resources (see Table 1) offer the largest bioCCS integration potential as these fractions represent a very high volume combined with a significant carbon content, are readily combustible, and are part of well-established value chains.

Finally, it is worth noting that the Norwegian forest has significantly grown over the last century despite a steady rate of logging. Even though not considered in the wood estimates presented in Table 1, further extraction and integration of this biomass with bioCCS could take place while maintaining the current size of the Norwegian forest. It is estimated that harvesting of forestry biomass could be increased by up to approximately 50% compared to today's level without any reduction in forest standing volume [13]. This integration could guarantee that the removed CO_2 by this biomass growth is permanently prevented from returning to the atmosphere in the future.

3.1.3. Marine biomass

Macroalgae (seaweed) cultivation and use for bioenergy with CCS has been highlighted as an opportunity for negative emissions. Norway has a long coastline and strong industrial traditions for fishing, aquaculture, and offshore activities. As such, seaweed production for various applications (from food additives to materials production) is emerging as a novel area of interest. It is currently in its early stages, with a few hundred tons produced yearly. However, it is forecasted to become a large industry in the coming decades with several ongoing research, development, and demonstration initiatives. However, it is worth noting that macroalgae has high water (above 80%) and salts contents which may pose challenges regarding stability, transport, and ultimately conversion to bioenergy [15].

3.1.4. Waste biomass

Different waste fractions containing biomass are currently being produced within the Norwegian society: 1) Wood waste, mostly demolition wood of various qualities2) Sewage sludge from wastewater processing 3) Waste from aquaculture (e.g., fish waste, silage, and sludge) 4) Wet organic waste from households[3] 5) Wet organic waste from

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[2] For example, for drying purposes.

[3] New EU regulation requires separate collection and treatment of organic waste starting January 1st, 2023 with a focus on material recycling.

Table 1
Quantities of Norwegian biomasses produced in 2020 and their relevant characteristics.

Category	Biomass fraction	Total amount (kt)	Content (wt%)		Total carbon (kt)	Share integrable with bioCCS (%)[b]	Negative emissions potential (ktCO$_2$)
			Moisture	Carbon (d.b.[a])			
Agriculture	Livestock manure	9563	90	35.9	343	42%	528
	Straw	650	15	46	254	26%	242
Forestry	Timber to non-energy products (incl. export)	9876	50	49.8	2457	0%	0
	Bark	704	31	49.1	239	100%	875
	Timber-processing residues and logs[c]	3118	50	47.4	738	34%	921
	Residues from urban expansion	331	46	49	87	100%	319
	Branches and tops	4582	50	51.2	1173	70%	3010
	Stumps and roots	5394	50	47.4	1278	0%	0
Marine	Macroalgae	0.25	87	31.5	0.01	100%	0.037
Waste	Wood waste[d]	674	50	49.8	168	82%	504
	Sewage sludge	608	76	28.3	41	100%	151
	Fish waste	157	75	45.3	18	100%	65
	Fish silage	101	75	45.3	11	30%	13
	Fish sludge	126	75	45.3	6	100%	21
	Wet organic waste from households	440	69	46.8	64	50%	117
	Wet organic waste from industry	1301	69	46.8	188	13%	90
	Mixed waste to Waste-to-Energy	1800[e]	-[f]	27.2[f]	491	60%[e]	1077
	Exported waste[g]	1087	50	50	272	0%	0

[a] d.b. stands for dry basis.
[b] Discussions on how these values were set can be found in the supplementary information.
[c] Logs for wood stoves. Residues to bioenergy.
[d] Also called demolition wood.
[e] Total amount includes a fossil fraction (estimated to 40% of the total carbon content).
[f] Moisture content data not available for "mixed waste". A commonly accepted carbon percentage of 27.2 on a wet basis was considered as the combustion of a tonne of mixed waste produces around one tonne of CO$_2$.
[g] Combustible waste, mainly demolition wood and household waste. The total amount includes fossil fraction.

industry (e.g., food processing, slaughterhouses) 6) Mixed waste[4] to waste-to-energy plants 7) Exported waste.[5]

The last three fractions, together with wood waste, are the largest ones both in terms of annual production (nearly 4.2 million tons per year) and carbon quantities. However, the ones with the largest potential for integration with bioCCS are the mixed waste currently treated in WtE plants, as well as wood waste.

The fact that the waste sector is well-established could be an advantage as it implies that collection, transport, storage, and central solutions are in place and could be expanded upon.

3.2. From bioresource mapping to realistic negative emissions potential

3.2.1. Maximum theoretical negative emission potential

As indicated earlier, even if several bioCCS projects are currently under development, it will likely take a few years before large national deployments could take place. Thus, it is important to account for the evolutions in production of the biomass considered when estimating the maximum theoretical negative emissions potential of bioCCS in Norway. Based on historical data for each sector (as further discussed in Supplementary Information), this maximum theoretical potential was estimated to reach 9.5 MtCO$_2$/y in 2030 in a business-as-usual scenario, as illustrated in Fig. 3. This is around 20% higher than the potential based on the 2020 situation, due mainly to further growth of forestry biomass. Overall, the negative emission potential is primarily linked to biomass from forestry sources (mainly from residues, and branches and tops) and waste (mainly from mixed waste used in WtE plants and wood waste), which represent respectively 69 and 23% of the business-as-usual potential. The remaining 8% are linked to agricultural residues, while the potential of seaweed is currently insignificant in comparison.

The maximum negative emission potential increases significantly in the expansion scenarios. Compared to the 2030 business-as-usual scenario, the maximum negative emission potential increases by 21% and 88% in the expansion and bioCCS-driven expansion scenarios, respectively. In the expansion scenario, this increase is mainly driven by the harvesting of the forest to its balance quantity, which is responsible for half of the increase in maximum negative emission potential. Additionally, the shift from export to local energy recovery of large waste fractions and the potential development of seaweed farming are each responsible for a quarter of this increase. The 6.3 MtCO$_2$/y increase in removal potential between the expansion scenario and the bioCCS expansion scenario is linked to how the additionally harvested forestry biomass is used. In the expansion scenario, this additional forestry biomass resource is assumed to follow the same fates (i.e. uses), proportionally, as today. In the bioCCS-driven expansion scenario, all these additional forestry resources are assumed to be connected to bioCCS.

Considering the multiple and diverse contributions to these maximum potentials for negative emission potential from bioCCS identified for Norway, it is worth reflecting on the challenges and opportunities of integrating these different types of biomasses with bioCCS.

The integration of residues from the agricultural sector could enable limited potential in terms of quantities, although not insignificant. However, the high-water content of manure, which represents a large portion of the agriculture-related potential, could result in higher transport costs and the need for drying or the further development of conversion pathways able to cost-efficiently handle high water contents and potential additional impurities (e.g. sulfur) [17]. On the other hand, despite these biomasses being widespread all over Norway, their recovery could likely be facilitated by other transport activities in the

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[4] A mixture of household, commercial, and industrial wastes which is normally sent to incineration for the destruction of contaminants and energy recovery.

[5] A significant tonnage of Norway's combustible waste (mostly wood and mixed waste) is sent abroad, mostly to Sweden, where it is incinerated with energy recovery.

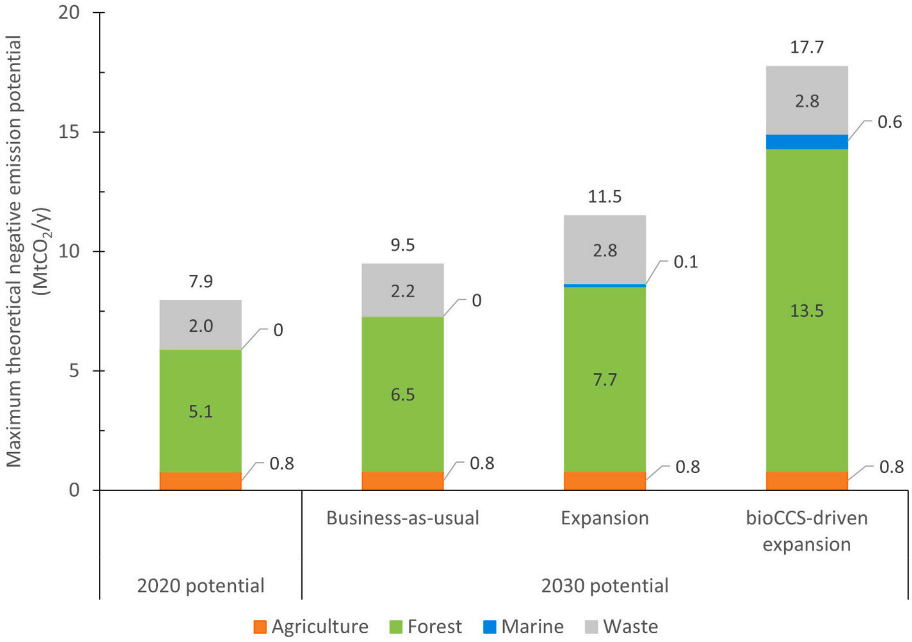

Fig. 3. Maximum theoretical negative emissions potential for the different scenarios considered.

agriculture sector. Finally, integrating these residues with bioCCS could also further valorize the agriculture sector in Norway.

The integration of forestry biomass with bioCCS represents the largest opportunity for negative emissions (between 67 and 76% of the overall potential, depending on the scenario). Forestry biomass has a reasonable water content, limited impurities, the technologies for its conversion to bioenergy (heat, power, hydrogen) is overall mature, and is part of a well-established industry and logistics. While the integration of residues[6] from current forestry biomass extraction appears to be a low-hanging fruit with a maximum potential of about 5 $MtCO_2/y$, the implications of expanding forestry biomass harvesting in terms of permanent carbon removal from the atmosphere [18], in terms of sustainability, biodiversity [19], etc. must be further investigated, and may impact the overall negative emission potential.

If the seaweed farming industry expands in Norway, the integration of seaweed with bioCCS could play a role in delivering negative emissions, although the 2030 potential seems limited. There are, however, several challenges to this integration that must be addressed. The high-water content will result in the need for drying or the development of conversion process able to handle it (e.g., hydrothermal treatments) [20,21]. The high salt content may lead to corrosion or result in the need to blend the seaweed with other biomasses before further processing. Finally, while at-sea farming avoids competition for the use of arable land, it may also increase production and collection costs [22].

Integration of waste biomass with bioCCS presents a significant potential for negative emissions. In addition, as a third of it is already being integrated with energy production (in waste-to-energy plants), part of this potential appears to be a low-hanging fruit [23]. BioCCS from waste presents the advantage of building on a well-established industry, would enable low-carbon handling of waste, including fossil carbon, and the sector's interest in creating a new revenue stream. On the other hand, the heterogeneity of waste, current regulations, impurities, etc. might impact the overall potential negatively.

In addition to the above biomass-specific aspects, several factors, such as the overall economic and policy framework, fossil emissions associated with deployment and operations of bioCCS, amay also reduce this overall potential [24]. Finally, these biomasses may also be sought for other applications than bioCCS [25,26]. For example, these may be used to produce liquid fuel for the maritime and aviation sectors, as a sustainable carbon feedstock in the chemical industry, or even for food applications in the case of seaweed.

3.2.2. *Negative emission window*

While the maximum negative emissions numbers discussed in the previous section provide a rough theoretical upper bound of the level of negative emissions that could be produced from Norwegian biomass resources, several factors may affect the amount of negative emissions effectively implemented and delivered. A more realistic negative emissions window is thus derived from this theoretical upper bound by taking into account two categories of factors impacting the realization of this maximum potential, as illustrated in Fig. 4: 1) the level of access to biogenic carbon[7] compared to the theoretical upper bound (X-axis) and 2) the level of negative emissions deployed from a set amount of biogenic carbon available (Y-axis). While the first point seeks to reflect challenges related to competition for biomass resources and social acceptance of certain biomass use, the latter category reflects potential challenges related to economic and policy frameworks, logistics, conversion technologies, and the greenhouse gas emissions generated during the deployment and operations of bioCCS solutions. For each of these two categories, three levels are considered. For the access to biogenic carbon, the three levels of access to the maximum potential identified in the bioCCS-driven expansion scenario (the scenario with the highest negative emission potential) are adopted: 1) 90% of the overall biogenic carbon to reflect a case with very little competition for biomass and/or a high interest in negative emissions, 2) 18% of the overall biogenic carbon to reflect a case considering only low hanging fruits, i.e. biomasses already integrated with bioenergy production, 3) 50% of the overall biogenic carbon to represent an intermediary case. In terms of the level of negative emission from a set quantity of biogenic carbon, the three levels considered are the following: 1) 80% corresponding to technical, economic, and policy framework very favorable to the implementation of bioCCS and with limited fossil emissions along the chains, 2) 25%

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[6] Including branches and topes, and residues already used for bioenergy.

[7] As the content of biogenic carbon varies significantly between biomasses, it is important to consider quantities of biogenic carbon rather than quantities of biomass.

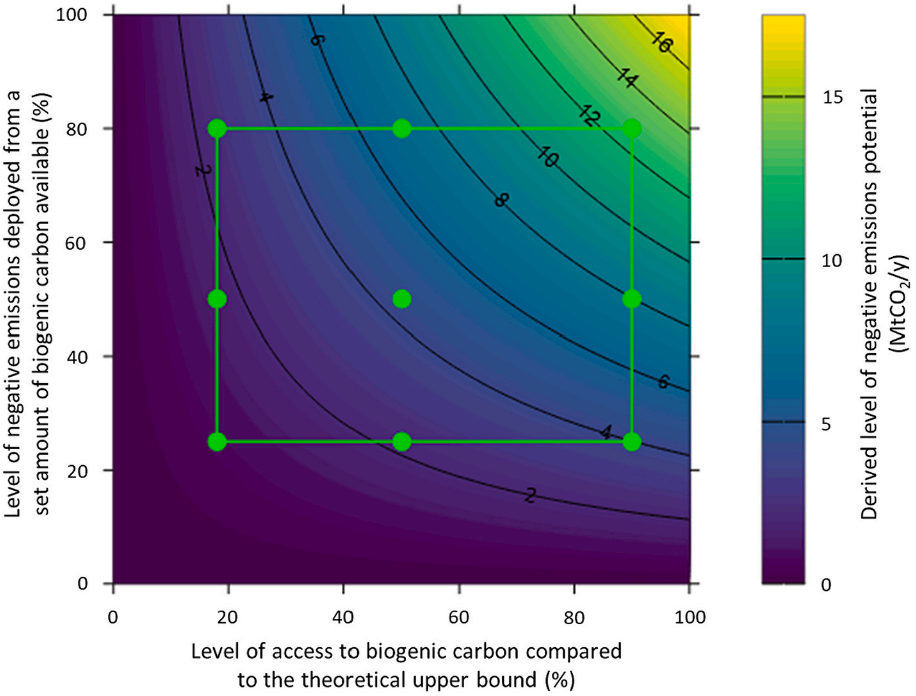

Fig. 4. Derived negative emission potential in function of (1) the level of access to biogenic carbon and (2) the level of negative emissions deployed from a set amount of biogenic carbon available.

corresponding to a framework with limited incentives for bioCCS, 3) an intermediary framework resulting in a 50% on negative emission deployment. The combinations of these scenarios result in negative emission potential windows illustrated in Fig. 4.

The negative emissions potential lies between 0.8 and 12.8 Mt. of negative emission per year for the set of nine possible combinations considered, with most of these combinations laying between 1.6 and 8 Mt. per year and the combination of middle levels reaching 4.4 Mt. per year. These numbers are quite significant considering that Norway's annual CO_2 emissions in 2022 were around 49 $MtCO_{2,eq}/y$ [27]. While there is currently no specific target for negative emissions from bioCCS set by Norway nor the European Commission, despite the strong interest in enabling these, these numbers are also interesting to put in a global context. The IEA's net-zero by 2050 roadmap [4] considers that 255 and 1375 $MtCO_2$ are captured from biogenic sources worldwide in respectively 2030 and 2050. This would mean that Norway could deliver between 0.6 and 1.7% of the global 2030 target if levels between 1.6 and 4.4 Mt. are reached.

Meanwhile, Norway could provide 0.3 to 0.9% of the 2050 target if levels of negative emissions between 4.4 and 12.8 Mt. per year are reached. While this contribution might be seen as small, it is important to remember that Norway represents a mere 0.1% of the world's greenhouse gas emissions, 0.07% of the world's population, and 0.3% of the world's land surface. This indicates that Norway could not only cover its share of negative emissions via bioCCS but also deliver negative emissions for other nations and/or compensate for part of its historical emissions.

Considering the strong focus in Norway on deploying bioCCS through multiple projects investigating CCS in waste-to-energy plants, as well as integration of both biomass use and CCS in industrial plants, around 0.5 Mt./y of CO_2 from biogenic sources could be delivered before 2030 [28,29]. However, it is unlikely that the higher ranges of this negative emission window could be unlocked within the coming decade due to the need to put in place a suitable economic and policy framework, as well as the time required to deploy such value chains. However, it is reasonable to expect that a significant share of this potential could be achieved in a 2040–2050 perspective if suitable economic and policy frameworks are put in place.

4. Conclusion

While bioCCS has been highlighted as a key contributor to the much-needed negative emissions to achieve the net-zero target, a better understanding of its potential is required to support scale-up. As such, ground-up approaches, starting from regional, national and continental biomass mapping, are necessary to understand the realistic potential of negative emissions from bioCCS and how these could be enabled.

Such a ground-up approach is here applied to Norway to understand the potential of bioCCS to deliver negative emissions. The results indicate that bioCCS could enable between 1 and 13 $MtCO_2/y$ of negative emissions, with a more probable range between 2 and 8 $MtCO_2/y$ at least in the coming decades. These values are drastically higher than the potential identified in previous studies. For example, Rosa et al. [16] indicated a nearly inexistant potential in Norway. Such discrepancies highlight the importance of bottom-up approaches, like the one adopted here, to better estimate the potential negative emissions from bioCCS.

In terms of biomass, the strongest potential comes from the integration of forestry resources and activities with bioCCS. This potential can be significantly increased if a bioCCS-driven expansion of forestry biomass harvest takes place. However, it is important to ensure that it takes place in a sustainable way and does not result in a decrease in the standing volume of the Norwegian forest for multiple reasons. Integrating waste with bioCCS also represents a significant potential, especially as a substantial fraction is already integrated with energy production, for especially, district heating. Finally, biomasses from agriculture and seaweed farming are expected to have a limited potential, although seaweed farming could take a more significant role towards the second half of the century, depending on the development of this sector.

When putting the obtained numbers into a global perspective, this study highlights that Norway could deliver up to 0.9% of the 2050 target for negative emissions from bioCCS. This potential is significant when considering that Norway represents 0.1% of the world's greenhouse gas emissions, 0.07% of the world's population, and 0.3% of the world's land surface. This indicates that Norway could not only cover its share of negative emissions via bioCCS but also deliver negative emissions for other nations and/or compensate for part of its historical emissions.

While these results highlight the strong potential of Norway to deliver negative emissions, several aspects require further attention to concretize it fully:

- Further knowledge on how to deploy bioCCS value chains in the Norwegian context must be obtained to understand the optimal integration of biomass resources with bioCCS, the preferred resulting energy products considering Norwegian specificities, associated costs and emissions, as well as the level of incentives required to enable deployment.
- Technologies for the conversion of relevant biomasses to highly decarbonizable energy products (heat, power, hydrogen) must be available. While this is likely the case for the conversion of forestry and waste biomass to heat and power, further development and maturation may be required for the conversion of wet biomasses from agriculture and seaweed farming, as well as for the cost-efficient conversion of biomass to hydrogen.
- Suitable policy and economic frameworks to achieve deployment must be put in place. This ranges from financial incentives to support the higher costs that arise with early movers, support cross-sector collaborations (biomass production, energy production, carbon capture and storage), establishment of certification framework, and high-quality carbon offset markets, etc.
- Finally, aspects related to sustainability and social acceptance of bioCCS, especially when biomass is of forestry origin, and competition for biomass resources with other sectors such as biofuel or biochar production, as well as impact on biodiversity, resource recycling, etc. should also be better understood.

CRediT authorship contribution statement

Nikalet Everson: Conceptualization, Data curation, Formal analysis, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Michaël Becidan:** Conceptualization, Data curation, Formal analysis, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Simon Roussanaly:** Conceptualization, Data curation, Formal analysis, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Rahul Anantharaman:** Conceptualization, Data curation, Formal analysis, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Petronelle Holt:** Conceptualization, Data curation, Formal analysis, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Roger Khalil:** Conceptualization, Data curation, Formal analysis, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

None.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.susmat.2024.e00912.

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