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Incentivizing BECCS—A Swedish Case Study

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Negative carbon dioxide (CO_2)-emissions are prevalent in most global emissions pathways that meet the Paris temperature targets and are a critical component for reaching net-zero emissions in Year 2050. However, economic incentives supporting commercialization and deployment of BioEnergy Carbon Capture and Storage (BECCS) are missing. This Policy and Practice Review discusses five different models for creating incentives and financing for BECCS, using Sweden as an example: (1) governmental guarantees for purchasing BECCS outcomes; (2) quota obligation on selected sectors to acquire BECCS outcomes; (3) allowing BECCS credits to compensate for hard-to-abate emissions within the EU ETS; (4) private entities for voluntary compensation; and (5) other states acting as buyers of BECCS outcomes to meet their mitigation targets under the Paris Agreement. We conclude that successful implementation of BECCS is likely to require a combination of several of the Policy Models, implemented in a sequential manner. The governmental guarantee model (Model 1) is likely to be required in the shorter term, so as to establish BECCS. Policy Models 2 and 3 may become more influential over time once BECCS has been established and accepted. Model 3 links BECCS to a large carbon-pricing regime with opportunities for cost-effectiveness and expanded financing. We conclude that Policy Models 4 and 5 are associated with high levels of uncertainty regarding the timing and volume of negative emissions that can be expected—Thus, they are unlikely to trigger BECCS implementation in the short term, although may have roles in the longer term. Based on this study, we recommend that policymakers carefully consider a policy sequencing approach that is predictable and sustainable over time, for which further analyses are required. It is not obvious how such sequencing can be arranged, as the capacities to implement the different Policy Models are vested in different organizations (national governments, EU, private firms). Furthermore, it is important that a BECCS policy is part of an integrated climate policy framework, in particular one that is in line with policies aimed at the mitigation of greenhouse gas (GHG) emissions and the creation of a circular economy. It will be important to ensure that BECCS and the associated biomass resource are not overexploited. A well-designed policy package should guarantee that BECCS is neither used to postpone the reduction of fossil fuel-based emissions nor overused in the short term as a niche business for "greenwashing" while not addressing fossil fuel emissions.

Keywords: bioenergy carbon capture and storage, negative emissions, incentives, policy instruments, policy sequencing, carbon dioxide removal

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INTRODUCTION

Carbon Capture and Storage (CCS) has been analyzed extensively in the context of mitigating carbon dioxide (CO_2) emissions from fossil fuel-based processes. More recently, there has been growing interest in applying CCS to biogenic CO_2 emissions, i.e., so-called BioEnergy Carbon Capture and Storage (BECCS), although it had already started to be discussed as a concept in the late 1990s (Williams, 1998; Möllersten and Yan, 2001; Keith and Rhodes, 2002; Möllersten et al., 2003). BioEnergy Carbon Capture and Storage can serve to offset residual emissions in hard-to-abate sectors (e.g., agriculture, shipping, heavy road transport) and to contribute to net-negative emissions on a global level (Obersteiner et al., 2001). Both effects are likely to be required because emissions levels will probably exceed what is compatible with the Paris Agreement (Intergovernmental Panel on Climate Change (IPCC)., 2018). In fact, BECCS is the major technology for carbon dioxide removal (CDR) in the vast majority of scenarios that are considered to have a high likelihood of meeting the terms of the Paris Agreement (Rogelj et al., 2018). Thus, although other CDR technologies exist, such as direct air capture (DAC) and land use change and forestation, these are less-developed (DAC) or highly complex (land use change).

According to Sweden's climate target, greenhouse gas (GHG) emissions should be at a net-zero level by Year 2045 (Swedish Government, 2017). This translates into a reduction of domestic (production-based) emissions of at least 85% (relative to the level in Year 1990), and offsetting up to 15% of emissions, corresponding to approximately 11 $MtCO_2e$, through the use of so-called "supplementary measures." These measures include increased sequestration of carbon in forests and agricultural land, verified emission reductions ("offsets") in other countries, and BECCS.

Proposed BECCS Targets for Sweden

A recently conducted public inquiry in Sweden ("SOU2020:4") has examined the supplementary measures (Swedish Government, 2020) and has concluded that it will be more costly to reach the target of net-zero GHG emissions by Year 2045 without the supplementary measures, since it would require comprehensive transformation of the agricultural sector (e.g., to mitigate methane and nitrous oxide emissions). The governmental inquiry has identified BECCS as the most promising supplementary measure with the largest volume potential and has proposed targets for BECCS of up to 2 $MtCO_2$/year by Year 2030 and 3–10 $MtCO_2$/year by Year 2045. The wide range estimated for 2045 reflects the uncertainty regarding the need for supplementary measures in Year 2045, i.e., uncertainty related to the contributions from other GHG reduction measures.

The SOU2020:4 inquiry concludes that supplementary measures often involve investment-intensive projects that run for a long time. For such projects to be realized, the field of measures needs to be characterized for stable terms and conditions and clear targets, with the aim of reducing the project-associated risks for the involved actors. The inquiry further suggests that the volume of supplementary measures should be gradually increased, and that an early start in implementing these measures will provide flexibility in relation to mitigation options in the longer term.

The inquiry also notes that a policy for incentivizing BECCS should promote technological development and demonstration activities, while at the same time creating long-term economic conditions for full-scale BECCS projects. It concludes that Sweden should act to ensure that the EU develops a common long-term instrument to promote BECCS.

Swedish BECCS Potential

The total potential for BECCS in Sweden is substantial, as the country has many large-point sources of biogenic CO_2 emissions, mainly combined heat and power (CHP) plants burning wood waste from the forest industry and pulp and paper plants (Karlsson et al., 2017). The aforementioned SOU2020:4 governmental inquiry estimates the total biogenic CO_2 emissions from point sources larger than 0.1 Mt to amount to more than 30 $MtCO_2$ per year. Johnsson et al. (2020) have estimated that the total for the emissions that could be captured from the 28 industrial units (i.e., excluding the energy sector) with the highest levels of emissions (i.e., >0.5 Mt/year) is 23 $MtCO_2$ per year, of which around half is from biogenic emissions. This level of capture is linked to an estimated average cost of 80–140 €/tCO_2, including the costs for transport and storage (Johnsson et al., 2020). Karlsson et al. (2017) have estimated the total potential for BECCS as 23.7 Mt, applying a capture rate of 85%, which corresponds to the capture of 20.1 Mt of CO_2 of biogenic origin. If only considering technologies at a cost below 120 €/ton, the total potential would be 16.7 Mt/year (Karlsson et al., 2017).

In principle, there is little difference between technologies that capture fossil-origin emissions and biogenic emissions. There is a large body of literature on CCS (see for example the *International Journal of Greenhouse Gas Control Technologies*), investigating the various technological and cost aspects of such technologies (capture by means of pre-combustion, oxyfuel, post-combustion, chemical looping combustion, etc.), including the transport and storage of the captured CO_2. In addition, there are reports in the literature on the social acceptance of CCS (see Tcvetkov et al., 2019 for a review). A large part of this knowledge is applicable also to BECCS, although the aspects of the social acceptance of BECCS may differ from those of CCS applied to emissions from fossil fuels. The general public may perceive negative emissions technologies, including BECCS as a means to tamper with nature and Wolske et al. (2019) used this as an explanation for their finding that the support for BECCS (and DAC) was lower than support for afforestation and reforestation. Cox et al. (2020) performed a study on public perception on CDR technologies in the US and UK from which they conclude that the need for CDR is perceived as a too slow a response to climate change and interpreted as not addressing the root causes of climate change. Bellamy et al. (2019) conclude that that the type of policy instrument used to incentivize BECCS influence perceptions of the technology where the public may favor coercive instruments over price guarantees for producers selling BECCS derived energy.

The post-combustion capture technology is a commercially available technology that has been used in the chemical industry for several decades (Bui et al., 2018) and which is also applied in current CCS schemes. In Year 2020 there were 26 commercial CCS projects in operation around the world (Global CCS Institute, 2020), having a total capture capacity of around 40 $MtCO_2$/year, although most of them are concerned with Enhanced Oil Recovery (EOR), for which the CO_2 is used to extract more oil.

With respect to BECCS, there is a substantial body of literature on its potential roles in global emission scenarios, typically based on Integrated Assessment Models (IAMs), e.g., Rogelj et al. (2018), Bellamy and Geden (2019), Fuhrman et al. (2019), Gambhir et al. (2019), Gough and Mander (2019), Forster et al. (2020), and Laude (2020). However, there has been little actual implementation of BECCS—even less than for CCS. Fuss and Johnsson (2021) have concluded that there is an obvious gap between the need for BECCS as identified in global IAM scenarios and its actual implementation. This type of implementation gap is also evident in Sweden, where no BECCS has yet been implemented, despite the favorable conditions for BECCS.

Fridahl et al. (2020) have presented an overview of existing policy instruments (economic, regulatory, and informational) for BECCS with a Swedish focus, and they conclude that at present there are only supply-push incentives in the form of support for demonstration of BECCS, whereas demand-pull instruments are lacking. Although a survey among UN climate change conference delegates, showed low prioritization of BECCS relative to alternative technologies (Fridahl, 2017) there is an increased interest in BECCS among Swedish stakeholders in industry and in politics.

Considering the explicit targets proposed in the above mentioned public inquiry (Swedish Government, 2020), there is a need for prompt introduction of economic incentives, in the form of demand-pull incentives, to support the commercialization and deployment of BECCS (Fridahl et al., 2020, Fuss and Johnsson, 2021). However, it is not obvious how incentives for BECCS can and should be introduced and ramped up over time and Bellamy et al. (2019) concluded that that public support for BECCS is linked to attitudes toward the policies through which it is incentivized. Based on stakeholder interviews around four different scenarios, Bellamy et al. (2021) have discussed what these scenarios might mean for BECCS, and they argue that policies should account for diverse and geographically varying societal values and interests. Although these works all argue in favor of policies that incentivize BECCS, there is a gap in the literature with respect to studies that propose and dissect explicit policies for BECCS (and other CDR technologies for that matter) and how these can be ramped up over time. Therefore, the aim of the present paper is to discuss different models for creating incentives and financing for BECCS. For this, we use Sweden as an example, given its favorable conditions for BECCS.

Challenges for Incentivizing BECCS

Since BECCS will require substantial upfront investments and additional energy and will, thereby, increase the production cost (e.g., for heat and electricity and pulp and paper), it is important that the BECCS policy is sustainable in the long term in terms of the level of incentives, as well as predictability. This has been a general problem for several capital-intensive mitigation technologies, including fossil CCS for which the EU ETS system has, so far, given insufficient incentives for large-scale implementation. The price of emissions allowances has been too low and too unpredictable to trigger investments in CCS and other more-transformative technologies. Another characteristic of BECCS (and CCS) is that although BECCS is largely based on a commercially available technology [high technology readiness levels (TRLs) for post-combustion capture technologies], it cannot be ramped up in an incremental way (as is the case with wind and solar power) but instead requires large-scale units. Thus, any policy must be able to deal with this.

There are, at least, two explicit challenges associated with creating policies for incentivizing BECCS (or other CDR technologies), the first of which has previously been identified in the literature:

1. That the possibility for widespread deployment of BECCS later in the century may reduce the effort for deep near-term mitigation of fossil fuel emissions (Anderson and Peters, 2016), possibly locking Society into a high-temperature pathway if BECCS (or another CDR) fails to deliver at the required levels (e.g., Anderson and Peters, 2016; Obersteiner et al., 2018).
2. The creation of a near-term BECCS policy that is strong enough to trigger its implementation may require incentives that are higher than the cost of emitting fossil fuel carbon. This may result in inefficient use of biomass, which is a limited resource that is also needed for other purposes.

Regarding the first point above, recent publications by McLaren et al. (2019) and Geden and Schenuit (2020) have discussed the negative impacts that promises of negative emissions could have on emissions reduction, and they have proposed the development of separate targets for emission reductions and negative emissions, so as to minimize the risk that there will be less emphasis on fossil fuel mitigation due to the future availability of BECCS. Yet, the authors of the present work believe that, although the first point above is logical and may entail a risk of delaying near-term mitigation, it is somewhat theoretical in that, in practice, the present lack of a sufficiently strong climate policy does not seem to be due to the fact that actors in Society (firms or policymakers) are betting on future possibilities for negative emissions. This contrasts with the second point above, which is more or less already a reality in Sweden where energy, transport, and industrial actors all envision the use of biomass as an important mitigation measure, at the same time as there is a proposal to establish explicit target for BECCS for Year 2030 (Swedish Government, 2020). The proposed BECCS targets would require BECCS incentives of at least 100 €/tCO_2, or more likely 150–200 €/tCO_2 in the short term, before adequate experience is gained (cf. the costs given by Johnsson et al., 2020). This is far higher than the present cost to emit fossil fuel-derived CO_2, which at the time of writing is at 56 €/ton within the EU ETS (European Energy Exchange, 2021). Although this is the highest valuation so far, the future trajectory of allowance prices is uncertain (considering that allowance prices may decrease again). Thus, there is a risk that an asymmetry will be created between the cost of reducing fossil fuel emissions and the compensation assigned for negative emissions.

It can be concluded that there is a need for a climate policy that is sufficiently potent to trigger the required reduction in fossil fuel emissions at the same time as incentives for negative emissions are created that support the large-scale demonstration and development of BECCS. This is in line with Bednar et al. (2019), who have proposed that a mitigation strategy that includes CDR should build on the following two pillars: (i) earlier and more radical reductions in emissions than what most Paris Agreement-compliant mitigation scenarios suggest; and (ii) near-term development and ramping-up of CDR technologies to clarify their actual potentials and the scaling properties of specific technological options. The authors argue that CDR should primarily be regarded as a tool for hedging against climate-related uncertainties. Fuss and Johnsson (2021) have argued that a balance must be established between valuing negative emissions achieved through BECCS and the cost of fossil fuel-related emissions.

In summary, there is an urgent need to analyze how CDR can be incentivized. This paper is a first attempt to assess different Policy Models with the focus on BECCS in the Swedish context. We chose BECCS because this is the most-mature CDR technology for which—as indicated above—concrete targets have been proposed in a Swedish public inquiry.

ASSESSMENT OF BECCS POLICY MODELS

Choice of Policy Models

A common way to create incentives for reducing the environmental impact of emissions is the so-called Polluter Pays Principle, PPP (Organisation for Economic Co-operation and Development, 2021). *Polluter Pays Principle* includes the pricing of CO_2 emissions and other pollutants in the form of a tax or a trading system, such as the European Union Emissions Trading Scheme, EU ETS (European Commission, 2003). However, with negative emissions, PPP is not applicable, since there is no pollution, but instead a common benefit (or a *positive externality)*. Since carbon removal results in a common benefit, it can be argued that it should be taken from the state budget (although for a global common benefit there are no corresponding global "state budgets"). If one wants to formulate a principle analogous to PPP, this could be called the *Beneficiary Pays Principle* (BPP). This reasoning leads us to Policy Model 1, where the state procures a certain amount of BECCS. This model has also been proposed by the Swedish inquiry for supplementary measures (Swedish Government, 2020).

Although not strictly following the BPP, from a financing perspective, one could argue that those who emit fossil fuel emissions (or other GHGs) should contribute to financing BECCS. This could be implemented by imposing an obligation on those who emit to pay for carbon removal. Sectors that could be targeted for such obligations are those that account for significant emissions today and residual emissions in the future. This is our motivation for Policy Model 2 (quota obligation).

The Swedish BECCS potential is significantly larger than the estimated residual emissions in Sweden in Year 2045. Exploitation of the full potential of Swedish BECCS projects could be done by linking with international carbon markets. One way to do this is to allow the participants in the EU ETS to purchase BECCS credits as an alternative to emission allowances, which is the goal of Policy Model 3.

Policy Model 4 is based on offering BECCS credits to voluntary markets, which would be a way to broaden the funding of Swedish BECCS.

Based on these four models, the authors of this paper have participated in three workshops (12 February 2020 in Stockholm, 15 February 2021 online, 22 April 2021 online) to discuss the relevance and feasibility levels of the models. The participants in these workshops consisted of business representatives/potential BECCS operators, members of the Swedish parliament, government officials and academic experts. The workshops deemed the four models to be relevant and identified a fifth model (Policy Model 5: other states as buyers of BECCS credits).

In conclusion, we have identified the following five Policy Models for creating incentives and financing for BECCS in Sweden: (1) state guarantees; (2) quota obligations imposed on selected sectors; (3) EU ETS use of BECCS credits for compliance; (4) private entities for voluntary compensation; and (5) other states as buyers. These Policy Models, which are listed in **Table 1**, are analyzed and discussed regarding potential volumes, financing, governance, and stakeholder preferences.

Model 1: State Guarantees

With this Model, the state (i.e., the taxpayers) buys BECCS outcomes. This can be done through long-term agreements with BECCS producers, whereby the state guarantees to buy a certain level of carbon removal by BECCS over a certain time. To minimize costs to the state, the contracts can be auctioned off in lots to the lowest bidder. The previously mentioned Swedish public inquiry (Swedish Government, 2020) has proposed a system of Model 1 type in the form of a reversed auctioning system (reversed in the sense that there is one buyer of the credits—the Swedish state—and many potential sellers of negative emissions).

Potential Volumes and Financing

As an indicator of the required level of financing, the target of up to 2 Mt/year BECCS by Year 2030 for Sweden, proposed in the abovementioned government inquiry would entail a cost of 200 million € per year (Fuss and Johnsson, 2021), assuming a total BECCS cost of 100 €/tCO_2 (i.e., the costs estimated in Johnsson et al., 2020).

It is likely that the cost of the first full-scale capture projects will be higher than that for an N^{th}-of-its-kind plant (the bases for the costs given above). The first full-scale capture should be applied to large point sources of emissions, which are mainly

TABLE 1 | The five Policy Models for incentivizing BECCS investigated in this work.

Policy model	Primary financer	Motivation	Governance challenges drawn from the stakeholder workshops and identified in the related analysis
1. State guarantees	Swedish state	Favorable conditions can be created for ramping up BECCS facilities in accordance with near-term targets (e.g., to Year 2030).	Expensive for the state. Several firms expressed a strong interest in selling the credits to buyers on the voluntary market, which may be in conflict with the intention of the state to claim the outcome. Thus, the ownership of credits should be clarified prior to procurements. Risk for biomass resource depletion if applied in isolation from other policies. BECCS needs to be part of a broader strategy for the bioeconomy. May be challenging to reach acceptance for BECCS when using this model Bellamy et al. (2019)
2. Quota obligation	Sectors that emit GHGs, for instance transportation, waste, and agriculture	Broadens the financing basis. Reduced costs for the state compared to Model 1, which translates into increased public acceptability. Increased incentives for reducing fossil fuel use in transports, for reducing combustion of plastics and for reducing GHG emissions in the agricultural sector.	As transport-related emissions and plastics in waste are reduced over time (or from increased plastic recycling), so are the revenues to finance BECCS. As emissions from the transport sector are expected to be reduced, so will the revenues from the transport-based quota system. Thus, in the longer term, a quota obligation should target sectors with residual emissions, such as those from waste, agriculture, and aviation. Could facilitate public acceptance for BECCS in line with the findings of Bellamy et al. (2019)
3. Allowing participants in the EU ETS to use BECCS credits	EU ETS participants	Broadens the financing basis. Could lead to a significant demand for BECCS. Eventually will bring down costs for participants in the EU ETS.	Would require a major reform or amendment of the EU ETS Directive, since credits are not currently allowed in the EU ETS.
4. Private entities for voluntary compensation	Private companies, e.g., travel agencies	Can contribute to the deployment of BECCS. Expands the demand-base of the policy to include non-territorial carbon emissions, such as from international aviation and foreign companies. Would exert less pressure on governmental policies.	Although voluntary markets can contribute to early deployment, the Swedish state cannot count on this. Thus, if the state wants to support the development of BECCS other financing models will be needed. Voluntary markets could come on top of this. Need to address the risk for double claiming. Unless sold credits are subtracted from national mitigation targets there is a risk that global emissions may increase.
5. Other states as buyers	Other states		To prevent double counting, corresponding adjustments from national commitments need to be made.

The table also provides a summary of our analysis, presented in more detail in the following sections.

biomass-fired CHP units and pulp and paper plants. For such applications, the technology is new, and an initial learning phase will be required. Moreover, competition between technology providers is likely to be low and there may be costs related to uncertainty and internal risk. In addition, early transport and storage projects may have higher specific costs (€/ton stored-CO_2) than the subsequent, more-established transport and storage infrastructures, which may be shared between different users. In the Swedish case, initially, storage will most likely be purchased from Norway, and it is not obvious what the price will be in the longer run if there is competition for using this storage (i.e., the price for buying storage is not the same as the cost for storage). At present, Equinor (2020) estimates that the cost for transport and storage will be in the range of 30–55 €/tCO_2 referring to the cost given in IOGP (2019).

Governance

A major advantage of Policy Model 1 is that, in an initial stage, favorable conditions can be created to promote the establishment of the first BECCS facilities, given that long-term contracts with an agreed price per ton CO_2-sequestered create predictability for BECCS producers. Another advantage is that the state can have some control over how large a volume of negative emissions is produced through BECCS and when and for how long the state wants to support such production. Through long-term agreements, the state can decide in advance the volumes that it wants to buy, e.g., 2 Mt of BECCS reductions per year. Such predictability is most likely a prerequisite for operators to invest in BECCS. Long-term agreements in which the government undertakes to buy a large volume of negative emissions from one or more suppliers through auctions have the possible advantage that the price can be pressed downwards. However, one challenge will be whether or not the seller can deliver.

For BECCS (as for CCS), the option to start very small is unrealistic if the technology is to become implemented at the commercial scale. Thus, the first projects at commercial scale will require a high up-front investment and result in a higher operating cost (i.e., the product from the plant will be more expensive, albeit with no or negative carbon emissions). It will also be a challenge to ramp-up the technology in line with the Year 2030 target set in the public inquiry of supplementary measures (Swedish Government, 2020) as pointed out by Fuss and Johnsson (2021). In Sweden, projects are underway on biochar (char from the pyrolysis or gasification of biomass, which will be used as a soil additive), as well as initial projects using biomass waste fractions that are available for free (such as public gardening residues). These may offer carbon-negative outcomes at a lower cost than BECCS, albeit the potential in terms of volumes is low. Thus, the auctioning system should be designed to not only target such low-cost and low potential alternatives, but also to support the implementation of BECCS systems that have adequate duration and predictability. This is in line with the preliminary assessment of how an auctioning system could be designed, as issued by the Swedish Energy Agency (2021a). That report states that biochar should not be part of the auctioning system.

For Sweden to procure 2 Mt of BECCS per year will require 4–5 plants to be equipped with CCS, assuming typical plants with a size large enough to obtain the abovementioned specific cost for BECCS (i.e., emitting some 0.4–0.5 $MtCO_2$/year). There are pulp and paper plants that each emit more than 1 million ton of CO_2 and, thus, applying BECCS on those would only require two plants to reach the proposed 2 Mt BECCS target. However, it seems unlikely that the first BECCS applications would be on these plants. A key challenge for the government will be to match auction volumes with both the technical potential for BECCS in Sweden and the willingness of prospective BECCS operators to engage with auctions (Fridahl and Lundberg, 2021).

An alternative to auctioning is for the state to buy BECCS outcomes "per verified stored ton" at a fixed tariff. The main difference between this and auctioning is that the state decides the price per ton but then has limited control over how many ton will be purchased. The system can be compared to a negative tax, in the sense that the BECCS producer is paid for each ton of separated and stored CO_2. A fixed storage tariff, whereby the state pays per "verified stored ton," has the advantage that the state pays on delivery for the benefit performed, albeit with the disadvantage that it is difficult for the state to set an appropriate price level. With a too-low price, no volumes may be produced at all. Such a model will obviously rely on a sufficiently high price for carbon removal and that the high price is offered for long enough to establish sufficient predictability.

A state guarantee policy model may not be the best long term option for reaching acceptance for BECCS since Bellamy et al. (2019) concluded that the public may favor coercive instruments over price guarantees for producers selling BECCS derived energy.

Model 2: Quota Obligation on Selected Sectors With GHG Emissions

One can argue that sectors or activities for which it is difficult to mitigate GHG emissions should contribute to financing negative emissions, e.g., BECCS, if they cannot mitigate their own fossil fuel emissions. The state could impose an obligation on such GHG emitters to purchase BECCS credits corresponding to a share of their GHG emissions. In theory, such an obligation can be implemented on a one-for-one basis, meaning that 1 ton of emitted GHG requires the purchase of 1 ton of BECCS. However, a quota system on a one-to-one basis may constitute a significant cost for the participant. A more commonly used method—typically applied for renewable energy—is to apply a quota obligation starting at a level of 10% and thereafter ramp it up at a certain pace. The system is similar to the Swedish-Norwegian electricity certificates, which require electricity retailers to purchase renewable electricity certificates corresponding to a share of the sold electricity (Swedish Energy Agency, 2021b). It is not obvious for which sectors and emitters a quota obligation system would be an efficient policy instrument. Since BECCS offers negative emissions, it seems reasonable to assume that such a system could be an option for "hard-to-abate" sectors such as transportation (road, aviation, and maritime), waste and agriculture. It is not clear how these sectors should be defined. Thus, it may be that quota obligations will have to be offered to all emitters, and unless emitters can reduce emissions themselves, they will be obliged to purchase BECCS quotas.

Potential Volumes and Financing

Transportation is presently the largest emitter of GHG emissions in Sweden, with around 16 $MtCO_2e$ in 2019 (Swedish EPA, 2021). If, for example, this sector was to purchase quotas corresponding to 10% of their emissions, this would create a demand of 1.6 Mt of BECCS credits today. This corresponds approximately to the BECCS target proposed by the Swedish Government (2020) for Year 2030. This would increase the cost of gasoline by 2.9 eurocents (0.029 €) and the cost of diesel by 2.6 eurocents (0.026 €) (Zetterberg et al., 2019). As fossil fuels are phased out in the transport sector, the demand for BECCS credits should decrease.

A quota obligation fits well with the transport sector's challenge in meeting the Year 2030 target for emissions reductions, which is set at 70% relative to Year 2010. Although there is ongoing electrification of road transport, with several car manufacturers stating that they will stop producing vehicles (passenger cars) with internal combustion engines (typically around Year 2030) and with sales of new electric vehicles increasing, the replacement of the current car fleet will take time, which makes the goal of a 70% reduction a challenge. At present, the yearly reduction in emissions from the transport sector (excluding international aviation) is around 2%, which needs to increase to around 8% to meet the Year 2030 target (Swedish

EPA, 2021). Heavy road transportation represents the greatest challenge, since for this sector electrification is not obvious, with hydrogen/fuel cell vehicles and electric road systems emerging as alternatives to battery vehicles, even if the development of these options is slow and their future seems uncertain at present with TRL levels estimated to 5–6 (Gnann et al., 2017). While decarbonizing road transport is technically feasible, the aviation and maritime transport sectors imply significant challenges for fuel shifting (Nordic Council of Ministers, 2016; Horvath et al., 2018; Gray et al., 2021). These sectors may need to offset their emissions before the appropriate technologies are sufficiently advanced to allow direct and deep emissions cuts. It should be mentioned here that (domestic) aviation is not included in the aforementioned 70% reduction target.

In the longer term, e.g., coming up to Year 2045 when Swedish GHG emissions should be net zero, it should be possible for the road transport sector to meet the zero-emissions target provided that the present rate of technological development continues for light vehicles and new technologies are introduced for heavy road transport (e.g., electrification, hydrogen fuel cells, electric road systems) and that the related CO_2 emissions are close to zero, which would entail a low demand for BECCS credits. Nonetheless, a quota system for negative emissions that includes the transportation sector may help establish the BECCS technology, which should be beneficial for Society.

Combustion of domestic waste and non-toxic industrial waste in Sweden produces approximately 400 kg fossil CO_2 per ton waste (Year 2017), totaling approximately 3.4 Mt fossil CO_2-emissions due to the plastic content in the waste (Zetterberg et al., 2019). If a quota obligation was to be imposed on 50% of the plastic-related emissions this would create a demand for 1.7 Mt of BECCS credits (Zetterberg et al., 2019). Assuming a total BECCS cost of 100 €/tCO_2, this would correspond to approximately 20 € per ton combusted waste (0.4 t · 50% · 100€/t), or 50 €/tCO_2 emitted, which is less than the price on EU allowances of 56 €/tCO_2 when writing this in June 2021 (European Energy Exchange, 2021). As with the transportation sector, it can be expected that the plastic content of waste will decrease over time, which means that the demand for credits will decrease. Swedish waste combustion facilities are, unlike those in most other EU Member States, included in the EU ETS and need to purchase emission allowances corresponding to the emissions generated by the combustion of plastics. Therefore, if a quota obligation is to be placed on emissions from plastics processed in combustion facilities, one could argue that these facilities should be excluded from the EU ETS.

It should, however, be mentioned that there is ongoing research on developing "plastic refineries" for recycling plastic, whereby pyrolysis or gasification processes are used to process plastic waste back to its original components in the form of olefins (Thunman et al., 2019). Such processes can also be equipped with CCS which, if powered by renewable energy and assuming a sufficiently high recirculation rate, would result in negative emissions.

Agriculture accounts for approximately 6.9 MtCO_2e in Sweden (Swedish EPA, 2021). The governmental inquiry SOU2020:4 (Swedish Government, 2020) concludes that it would be costly to reduce GHG emissions to close to zero in the agricultural sector, as this would require a comprehensive transformation of this sector, including the mitigation of methane and nitrous oxide emissions. Therefore, we can expect that the agricultural sector will have residual emissions in Year 2045, which would make it a natural target for financing BECCS, for instance through a quota obligation, at least in the long term.

A quota obligation model (Model 2) may be a more favorable policy model than Model 1 for reaching acceptance of BECCS since it will not directly involve taxpayer's money, which is in line with the conclusions by Bellamy et al. (2019).

Governance

A challenge associated with using the road transport sector to finance BECCS is that the emissions from this sector are expected to decrease significantly in the next 10 years (Swedish Government, 2017), which will reduce the financial base for BECCS. This decrease can be compensated by increasing the quota obligation gradually from 10 to 100%. As the aviation sector is also likely to have residual emissions during the entire period up to Year 2045, it could provide a financing base for BECCS, together with other sectors, such as agriculture.

As with the state guarantee, it will be a challenge to design a quota system that can deal with the fact that BECCS must be initiated on a relatively large scale (and not incrementally, as discussed above). Quota obligations can be powerful drivers for the upscaling of CDR, although they can generate significant costs for the affected entities. Lobbyists are, therefore, likely to attempt to block the introduction of such mandates; experience from other mitigation technologies is that, in general, only profitable technologies are subjected to mandates (Honegger et al., 2021).

Model 3: Allowing Participants in the EU ETS to Use BECCS Credits

With the current rules, the EU ETS cap will reach zero in Year 2058, meaning that the last emission allowance will be issued in Year 2058 (Elkerbout and Zetterberg, 2020). However, in 2019, the European Council decided that the EU's GHG emissions should reach net zero by year 2050 (with a 55% reduction target for Year 2030, as compared with the Year 1990 levels, European Council, 2019). This necessitates a strengthening of the EU ETS and brings forward the time schedule for issuing the last allowance, for instance to Year 2050 or earlier. This raises the question as to what will happen when the EU ETS cap approaches zero. As we get closer to the year with zero emissions, it is likely that there will be residual emissions, for which abatement will be expensive and/or technically difficult. In addition, the application of CCS to emissions from fossil fuels, foreseen to be applied to mitigate process emissions from industries (e.g., the cement industry), will not fully eliminate emissions due to the capture rates being below 100%. Aviation—which is partially included in the EU ETS—may likewise continue to emit GHGs well into the future. If so, an emissions trading system with a zero cap could still be possible if there exist credits that represent negative emissions and that can be used to compensate for the residual emissions in the ETS.

One problem is that, under current rules, imports of credits are not allowed in the EU ETS (European Commission, 2013). It is noteworthy that the EU ETS already allows for the use of fossil CCS to reduce fossil fuel-related emissions. This could be an opening for allowing BECCS to be implemented in the future.

Potential Volumes and Financing

In the document *A Clean Planet for all*, issued by the European Commission, there are scenarios in which BECCS is responsible for a significant share of the emissions reductions, in some scenarios as much as 180 Mt/year in the Year 2050 (European Commission, 2018).

From the Swedish perspective, it is difficult to predict what the demand for BECSS credits would be if such credits could be used in the EU ETS. The demand would depend on the cost structure in Sweden compared to other types of emission reductions within the EU ETS, as well as on the prospects of other incentives for negative emissions. As pointed out previously, Sweden has favorable conditions for BECCS, so if the demand/price is high enough it is conceivable that the entire Swedish potential will be utilized, i.e., the abovementioned 17–20 Mt of BECCS credits per year (Karlsson et al., 2017).

A major advantage of including BECCS in the EU ETS is that BECCS would be included in a broader carbon pricing regime. This would provide participants an additional option to comply and contribute to bringing down costs for the participants in the EU ETS. This may also create a significant demand for BECCS and providing opportunities for scaling up BECCS. However, it will take time before BECCS credits will become an attractive alternative to emissions reductions or the buying of EU ETS allowances. With a cost for BECCS of 100 € or more, an allowance price in parity with that cost will be needed for BECCS to become an alternative in its own right for the participants. Yet, such an allowance price is also required for fossil fuel emissions sources if we are to abate emissions, including the use of CCS.

Governance

Allowing the use of BECCS credits for the purpose of compliance in the EU ETS would require significant revisions to the EU ETS, as well as to the effort sharing regulation (ESR) and the land use, land use changes, and forestry (LULUCF) Directive (Rickels et al., 2021). An obvious challenge is that the emissions factor for biomass is zero (European Commission, 2003). Emissions and uptake of biogenic CO_2 are accounted for under the LULUCF regulation and are expressed as carbon stock changes. However, this contrasts with fossil CCS, as the EU ETS allows the use of CCS for reducing fossil emissions. This asymmetry could be an opportunity to integrate BECCS into the EU ETS.

Discussions on the inclusion of BECCS in the EU ETS would raise questions as to whether or not the use of BECCS credits should be restricted. While unrestricted use might confer a higher level of effectiveness (Rickels et al., 2021), there are concerns that firms will buy BECCS credits instead of reducing their (fossil) emissions. However, as mentioned above, with a cost for BECCS of 100 € or more, it will take an allowance price of 100 € or higher before BECCS becomes a viable alternative to reducing emissions.

An alternative way to include BECCS in the EU ETS would be to create a separate market for BECCS (and potentially also other CDR technologies). Demand could initially be created through procurement (analogous to Model 1) or different types of investment support, for instance through the EU Innovation Fund or through national programs. Once the system has been operational for some time, it could be partially linked to the EU ETS. The transfer of credits could, for instance, be restricted.

There is currently no roadmap for modification of the existing EU ETS with regards to the integration of CDR (Rickels et al., 2021). Looking to the future, if the EU ETS is to have a zero cap in Year 2050, this will require the use of some sort of credit system for offsets. Given the complexity of the issue, with long lead times for investments and several EU regulations that need to be adjusted, the inevitable debate should start as soon as possible.

If Sweden wants to pursue the development of a regulatory framework at the EU level that creates incentives for negative emissions from BECCS, as suggested in SOU2020:4 (Swedish Government, 2020), one way forward would be to cooperate with other Nordic countries that show similar ambition. This may well-turn out to be the case given the significant bioenergy resources (Sweden, Finland, Norway) and CO_2 storage capacities in the region, primarily in the North Sea (Anthonsen et al., 2013).

Model 4: Private Entities for Voluntary Compensation

Voluntary carbon markets started to emerge in the early 2000's in parallel with the development of the regulated carbon market under the Kyoto Protocol (Hermwille and Kreibich, 2016). Demand for offsets on the voluntary market is created by companies and individuals that wish to offset all or part of their carbon footprint without having legal requirements (Leonard, 2009; Hyams and Fawcett, 2013). The voluntary markets demand for offsets peaked around 2010 and thereafter the demand dwindled. Estimates based on surveys indicate that globally between 2005 and 2016, approximately 1 billion ton of CO_2 were offset on a voluntary basis (Hamrick and Gallant, 2017). In later years, interest in carbon offsets on the voluntary market has increased again as corporations adopt net-zero GHG targets that will require offsetting to meet their climate targets (Hamrick and Gallant, 2017). The transacted volume on the voluntary market in 2019 was larger than that in the earlier record year of 2010, mainly driven by corporate net-zero targets, and preliminary figures indicate that the volume in Year 2020 will reach even higher levels (Donofrio et al., 2020). Voluntary carbon markets could play a significant role in mobilizing the necessary private climate financing. In 2019, renewable energy and forestry represented the two major project categories for carbon offsets, with 42 and 36% market shares, respectively (by ton of CO_2 transacted) (Donofrio et al., 2020). Voluntary carbon markets already include CDR project activities (Honegger et al., 2021). Carbon dioxide removal types that have so far been adopted include, inter alia, forestation activities, biochar as soil amendment, enhanced soil carbon sequestration, wooden building elements, DAC technologies, and enhanced weathering (Poralla et al., 2021; PuroEarth, 2021). Once BECCS is implemented, BECCS credits could be included.

Potential Volumes and Financing

In estimating the potential demand for voluntary BECCS credits in Sweden, it is useful to look at Sweden's contribution to international aviation. Swedish air travel has a climate impact that corresponds to approximately 10 Mt CO_2-equivalents per year, including international traveling (Kamb and Larsson, 2018). If 10% of these trips were to be compensated by BECCS, this would correspond to a demand of about 1 Mt/year. This constitutes a significant demand, albeit one that is uncertain. The willingness to pay is also uncertain, especially if cheaper alternatives for carbon offsetting are available. Yet, other means of offsetting emissions (e.g., afforestation projects in other countries) are debated and have an unclear climate benefit. BECCS is less expensive than DAC with costs ranging from 250 to 600 USD (Lebling et al., 2021). Another potential disadvantage with applying BECCS as an offset measure is that it requires high levels of cooperation and trust between different sectors/companies. Direct air capture constitutes a stand-alone measure that could be managed by an independent party.

In the international setting, large companies such as Microsoft, Stripe, and Shopify have committed to becoming carbon-neutral and they have expressed intentions to purchase significant amounts of carbon credits, largely based on negative emissions (Honegger et al., 2021). Furthermore, some recent proposals regarding standards for corporate net-zero targets imply an emerging preference for the use of offsets based on negative emissions rather than offsets based on avoided emissions (e.g., Allen et al., 2020). If the companies that are seeking to offset their emissions were to develop an appetite for BECCS credits, this could create a significant demand for BECCS in Sweden and in other countries.

Governance

Selling BECCS outcomes internationally raises concerns regarding double counting and additionality (Honegger et al., 2021). If a company such as Microsoft (USA) purchases BECCS credits from a Swedish BECCS producer to be used to offset their corporate carbon footprint, there must be a system in place that ensures that the same negative emissions are not accounted for in both the producing country (Sweden) and in the country of the purchasing company (USA), since double claiming would undermine the integrity of the Paris Agreement (Schneider et al., 2014).

Voluntary carbon offset markets provide the opportunity to create a demand based on non-territorial carbon emissions, such as those from international aviation and foreign companies. A clear disadvantage of the voluntary nature of the demand is that the "demand signal" is uncertain (volume and price) and is in itself probably not strong enough to incentivize BECCS investments. Moreover, carbon offsetting is a net-zero game that does not lead to overall mitigation of global emissions unless it is exclusively applied by companies to offset residual emissions, in addition to the most-stringent mitigation schemes for their value chain emissions.

To date, the providers of CDR credits on the voluntary markets have applied very diverse approaches with regard to the methodologies used for calculating the removal of emissions, as well as with respect to monitoring, reporting and verification (Poralla et al., 2021). This situation might damage the long-term prospects of the international market for CDR credits. Regulatory oversight on the national level with regards to claims made on removal credits could improve this situation. Such an oversight system should focus on issues related to permanence and the quality of Monitoring, Reporting, and Verification (MRV). It should prevent the emergence of low-quality removal credit providers and the multiple claiming of the same activities' mitigation results (Honegger et al., 2021).

Model 5: Other States as Buyers

The Paris Agreement recognizes that some Parties choose to pursue voluntary cooperation with regards to the implementation of their National Determined Contribution (NDC), so as to allow for a higher level of ambition in relation to their mitigation and adaptation actions and to promote sustainable development and environmental integrity (United Nations Framework Convention on Climate Change (UNFCCC), 2015). International cooperation toward achieving NDCs falls under Article 6 of the Paris Agreement, which enables cooperation through market and non-market approaches. Article 6 lays out the requirements for transfers between Parties, including the rules for their robust accounting, thereby enabling carbon markets to service the Paris Agreement. Furthermore, "internationally transferred mitigation outcomes" (ITMOs) are defined, which can be produced through any mitigation approach provided that there is consistency with both the principles listed in Article 6.2 and the guidance provided by the Parties (Asian Development Bank, 2018).

The rules of Article 6 may, therefore, be relevant to a situation in which Country A funds carbon removals (capture and/or storage) in Sweden and Country A wants to claim (all or part of) the associated removal toward its target. In order to avoid double counting, Article 6 requires that a "corresponding adjustment" be made, which means that when Parties transfer a mitigation outcome internationally to be counted toward another Party's mitigation pledge, this mitigation outcome must be "un-counted" by the Party that agreed to its transfer (Asian Development Bank, 2018). The detailed rules for Article 6 have not yet been agreed by the Parties to the Paris Agreement. While Parties have made progress in the various negotiation rounds, several crucial issues remain to be resolved, including the notion of "corresponding adjustments."

Potential Volumes and Financing

Since net-zero emissions need to be reached on a global level eventually and the potential for negative emissions (that can offset residual emissions) is unevenly distributed, other nations may wish to purchase Swedish negative emissions from BECCS in the long term. It is, however, currently difficult to estimate the magnitude of such demand. The prices achieved in such a market might for a long time remain insufficient as stand-alone incentives for BECCS (Honegger and Reiner, 2018).

Governance

Within the Paris Rulebook, CDR needs to be considered systematically alongside emission reduction measures. In the Article 6 work program, methodological issues related to baseline setting, additionality, and MRV need to be prioritized. In the negotiations on the operationalization of the Enhanced Transparency Framework (United Nations Framework Convention on Climate Change (UNFCCC), 2015), accounting rules for removals need to be sufficiently specified (Poralla et al., 2021).

Regarding the Paris Agreement Article 6 market mechanisms, Article 6.2 may serve as an entry point for bilateral or plurilateral piloting activities that would allow for pre-testing elements of the market instruments (Möllersten et al., 2021; Poralla et al., 2021) thereby providing a proof of concept of such international cooperation on CDR.

Accounting and Monitoring, Reporting, and Verification

Monitoring, Reporting, and Verification along the BECCS value chain is necessary to quantify the mitigation outcome. The geologic storage of CO_2 requires special attention in this respect. Requirements or guidelines for monitoring are a key component of governmental regulations for CO_2 sequestration projects (e.g., the EU CCS directive). Numerous pilot tests and commercial operations have demonstrated the value of a wide range of monitoring techniques (Bui et al., 2018).

Several GHG MRV and accounting protocols and guidelines currently exist for CCS activities, and various activities are ongoing in this area. Such guidelines exist at the project, entity, state, country, and international levels, and work is ongoing to develop common accounting approaches (IEAGHG, 2016).

Any scheme that provides for the issuance of BECCS credits that can be traded needs to ensure that the verified negative emissions are additional and that double counting is avoided. A baseline needs to be established, against which the emissions reduction outcome is measured.

Swedish Preferences for BECCS Policies

One of the main obstacles to BECCS implementation is the lack of incentives for mitigating biogenic CO_2 emissions. The existence of this barrier has been confirmed by Swedish industry and government representatives (Bellamy et al., 2021). Regarding state support, some government officials have expressed the opinion that initiatives should be technology-neutral and that options other than BECCS, for instance large-scale afforestation and biochar, should be considered (Bellamy et al., 2021). Regarding EU-level policies, several business representatives have opined that EUA price volatility makes investments uncertain and that EU ETS reforms will take too long. As an alternative, they suggest innovation support, for instance through the EU Innovation Fund, as a better source of financing. It should be noted that in March 2019—the time of the study conducted by Bellamy and colleagues—the EUA price had recently increased from 5 € to 20–25 € per tCO_2 (and which had at the time of writing in May 2021, further increased to more than € 50 per tCO_2, although this is—as pointed out previously—still lower than the cost for BECCS).

A more recent study on preferences, performed in late-2020 and early-2021 (Fridahl and Lundberg, 2021), reveals strong interest in BECCS among Swedish business and government representatives. Several Swedish companies have already, or are currently, performing preliminary studies and/or have applied to the EU Innovation Fund for financing for BECCS. Given the choice between a tariff-based system and a reversed auction system, the majority of the actors prefer reversed auctions (Fridahl and Lundberg, 2021).

A disadvantage of state-funded acquisitions is that the system is expensive for the state and for taxpayers. As mentioned above, the auctioning system proposed in SOU2020:4 (Swedish Government, 2020) aims to reach 1.8 $MtCO_2$ per year in Year 2030 (a maximum of 2 Mt), after which it will be evaluated. An estimated cost of 180 million € per year to the state exchequer is unlikely to be sustainable in the long run. Studies have indicated that the level of public acceptance of state-funded procurement could be low (Bellamy et al., 2019).

Indeed, Fridahl and Lundberg (2021) conclude that virtually all the actors took the view that such a system would falter in the longer term. An ambition to maintain a state-led support scheme to scale up BECCS was deemed unlikely to attract sufficient political or public support, since the cost would likely be seen as prohibitive.

Regarding the preferences expressed by Swedish businesses and governmental agencies, Fridahl and Lundberg (2021) found that in the longer term, almost all the actors were in agreement that an incentive for BECCS should ideally be generated at the EU level. In this context, the EU ETS is presented as one option, even if this would require substantial amendments to existing legal provisions.

According to Stockholm Exergi (the municipal energy company of Stockholm), they already have customers that are interested in buying negative emissions quotas (Levihn, Pers. Commun.). Other firms state that they are not likely to invest while the prospects for selling to the private entities remain uncertain, unless they can engage in direct long-term contracts with large buyers. Several prospective BECCS operators in Sweden have expressed strong interest in selling the carbon removal credits to voluntary markets, even if they have received state support through auctions or other avenues (Fridahl and Lundberg, 2021). This may conflict with the intentions of the Swedish state.

ACTIONABLE RECOMENDATIONS

Based on our analysis of the five selected Policy Models, it is possible to make some recommendations to policymakers. However, more work needs to be carried out and these recommendations should be regarded as a starting point for work on developing robust policy packages with the aim of avoiding negative side-effects.

Sweden requires a BECCS policy that is predictable and sustainable over time (Fridahl and Lundberg, 2021).

Uncertainties regarding the level of support, size, and duration of BECCS may deter prospective operators from engaging in the further development of BECCS. At the same time, it is important that the BECCS policy is part of an integrated climate policy framework, and in particular that it is in line with policies for the mitigation of fossil-fuel based emissions and the evolution toward a circular economy. This is necessary to avoid the over-exploitation of BECCS and associated biomass resources (see Section Challenges of Incentivizing BECCS). A well-designed policy package should ensure that BECCS is not just a way to postpone reducing fossil fuel-based emissions (Anderson and Peters, 2016) and that is not used for "greenwashing."

With Model 1, whereby the Swedish state buys BECCS outcomes through long-term agreements with BECCS producers, favorable conditions can be created for the realization of several full-scale BECCS facilities. These are required to meet the target proposed in the SOU2020:4 inquiry, i.e., 1.8 Mt/year of BECCS by Year 2030. Yet, it seems important that the Government of Sweden decides on the purpose of the procurement/support. Is it to establish a new market with several operators that can grow over time or is it designed to purchase removal credits at the lowest price?

To reach the proposed level of 1.8 MtCO_2 per year in Year 2030, a BECCS policy needs to be introduced immediately, considering the lead times required to establish BECCS on a sufficient scale. Reaching 1.8 Mt MtCO_2 per year will require 4–5 plants, depending on type of plant used and if full or partial capture. As a low number of plants and operators may fulfill the full demand, this may cause challenges for establishing a competitive market, and the government will need to design carefully the auctions regarding the timing and size of auctioned lots, in order to engage prospective BECCS operators.

Several prospective BECCS operators in Sweden have expressed strong interest in selling carbon removal credits, either to private entities for voluntary compensation or to the EU ETS (Fridahl and Lundberg, 2021). If the intention of the proposed state-supported system is to purchase negative emissions and use them to meet the Swedish climate mitigation target, this needs to be specified and the risks related to the potential double claiming of mitigation outcomes need to be addressed.

State-supported BECCS could be instrumental in implementing the first BECCS operations in Sweden, although the basis for financing such an endeavor needs to be broadened so as to ramp up BECCS over time and reduce the cost to Swedish taxpayers.

It remains to be seen how a sufficiently strong policy for ramping up BECCS can be combined with other financing models and policies that develop over time. Model 2, which involves the imposition of a quota obligation, has the advantage that the costs for financing BECCS are placed on GHG emitters, thereby creating incentives for emitters to reduce emissions, as well as providing financing for BECCS. A possible challenge linked to imposing a quota obligation on the road transport sector is that emissions are likely go down over time, thereby reducing the financial basis for BECCS. In the longer term, this can be mitigated by directing the quota obligation toward sectors that are expected to have residual emissions, i.e., the agricultural, waste, and aviation sectors. It seems unlikely that potential producers will invest in BECCS without first receiving guarantees from the state. Model 2 may, therefore, be realistic in the medium-to-long term. However, the government may well-introduce a quota obligation earlier to raise revenues for financing BECCS through Model 1.

The feasibility of Model 3, which entails linking with the EU ETS, depends on whether imports of credits to the EU ETS will be allowed. If so, this would be part of a broad carbon pricing regime that would provide cost-effectiveness for ETS participants and create a considerable demand for BECCS in the long term.

If Sweden intends to pursue the development of a regulatory framework at the EU level that creates incentives for negative emissions from BECCS (as suggested by the inquiry regarding negative GHG emissions Swedish Government, 2020), one way forward would be to cooperate with other Nordic countries that show similar ambition. This may well-turn out to be the case given their significant bioenergy resources (Sweden, Finland, Norway) and storage capacities (Norway).

In case the EU ETS strategy proves unfeasible, Sweden should also investigate alternative policies at the EU level that can create markets for BECCS. Another reason for doing this is that in the long term, residual emissions are likely to come from sectors that are not included in the EU ETS (waste and agriculture).

Regarding Model 4, which involves private entities purchasing BECCS credits to compensate voluntarily for emissions, voluntary buyers (corporations) may create a significant demand for BECCS outcomes in the short and medium terms, and possibly also in the long term. However, the market is uncertain regarding both volumes and price. In any case, the development of the willingness of companies to include BECCS as a voluntary measure (Model 4) to reduce their emissions along their value chains should be closely monitored by government, since such measures would ease the pressure on governmental policies and reduce the cost to taxpayers.

Model 5, in which other states act as buyers of BECCS credits, may become an option. However, the use of credits from CDR that are to be applied toward national mitigation targets of NDCs cannot take place unless Article 6 of the Paris Agreement becomes operational. Governments that wish to take part in international transfers of negative emission credits should, therefore, promote the establishment of adequate modalities and procedures for MRV and accounting of CDR in the Paris Rulebook.

Policy Sequencing

The five different Policy Models discussed in this work differ with respect to the degree of certainty that they will create a specific level of demand for BECCS and, thus, the volumes that can be expected. It is likely that a policy sequencing approach will be required for successful implementation of BECCS. From a Swedish regulator's point of view, a logical sequence for the policies would be to start with the state buying BECCS outcomes in auctions as soon as possible (Model 1), followed by a phase-in of quota obligations to increase volumes and broaden the basis for funding (Model 2). If the EU ETS will allow participants to use BECCS credits to compensate for hard-to-abate emissions, this could create a significant demand for Swedish BECCS outcomes in the long term (Model 3). In addition, private entities (Model 4) may purchase BECCS credits to compensate voluntarily for emissions. With Model 5, other states may buy BECCS outcomes to meet their mitigation targets under the Paris Agreement or to increase their own ambition regarding emissions. Yet, Models 3, 4, and 5 are highly uncertain regarding their timing and expected volumes. This creates a challenge in that unless these models are ramped up, it will be difficult to phase out Model 1 and, thus, the state may have to assume a long-term commitment to support BECCS. Not all models may be required for successful implementation of BECCS. Model 1 will not be (economically) sustainable in the long run, but mainly fitted for establishing BECCS. It should be important that a strategy on a sequencing of different policy models is developed at an early stage so that markets actors will now what will happen once Model 1 will be phased out.

Figure 1 presents a schematic illustration on the timing of the five Policy Models. The volume levels are indicated only in relation to each other, with the aim of showing the approximate levels proposed in SOU2020:4 (Model 1), the long-term potential (17–20 Mt/year), and the proposed ambition (3–10 Mt/year in SOU2020:4). Although a sequential policy approach appears to be necessary, it is not obvious how it should be established, given that the capacities to act for the different Policy Models presented in this work lie with different organizations (national government, EU, private firms).

There are several possible interactions between the five models that can potentially strengthen or weaken their implementation. For instance, if the state would support the establishment of the first BECCS operators, this would facilitate for voluntary markets to procure credits and would help establishing a market price for BECCS. However, international buyers of credits could also become competitors to the Swedish state in the sense that they may procure large quantities of credits, some of which Sweden needs to fulfill its climate objectives. The establishment of a system of government procurement (Model 1) would contribute to developing a CDR certification mechanism for use in the EU and beyond, thus supporting models 3, 4, and 5. Yet, more work is required to understand likely interactions between policy models.

DISCUSSION

Implications of Swedish BECCS in a Broader Context

This paper addresses Policy Models aimed at incentivizing BECCS in Sweden. In addition to enabling ambitious national targets through BECCS deployment, Sweden can make contributions to a faster and environmentally more-credible advancement of BECCS (and potentially other CDR technologies) outside of Sweden, through pioneering BECCS incentivization. This will provide valuable guidance on how to develop effective instruments for the development of BECCS in jurisdictions other than Sweden, for instance in the EU. This in turn will enable the EU to deploy and ramp up BECCS on a larger scale. Stakeholder acceptance from early Swedish projects will also provide valuable experience for the international context.

If Sweden acts as an early mover in the implementation of BECCS, its practical experiences can make important contributions to the European Commission's efforts to develop a CDR certification mechanism. It could, furthermore, inform as to the lessons learned, which could be useful for the establishment of a proper MRV system if and when BECCS credits can be used in the EU ETS.

The lessons learned while establishing an MRV and accounting frameworks for BECCS could also make valuable contributions beyond the EU, for example toward the development of robust MRV approaches for the creation of CDR credits for voluntary carbon markets, and to ensure that accounting in the context of the Paris Agreement's Enhanced Transparency Framework is sufficiently robust to address the challenges of CDR (Poralla et al., 2021).

If Sweden pursues Policy Models that involve engagement with private actors that acquire BECCS credits for voluntary emissions compensation it could be shown how compensation can build upon high-quality emissions removal credits. This would include the establishment of conservative baselines and quantification of mitigation results, appropriate consideration of permanence, robust MRV, and the avoidance of multiple claims regarding the same activities' mitigation results.

Potentially Adverse Effects and Need for a Policy Package Assessment

Assuming that the Swedish state, another state or private firms are prepared to pay the full cost for BECCS, estimated to be at least 100€/ton, this may trigger some unwanted effects. It is likely that in a world—including Sweden—that moves in line with the Paris Agreement, the value, and thereby the price of biomass will increase. Thus, there will most likely be increased competition for biomass between sectors. A policy that incentivizes BECCS is likely to further increase the competition for biomass. Since an incentive for BECCS must be applied at probably at least 100€/tCO_2 over a considerable period of time (say up to Year 2030), it is important that policymakers evaluate how any BECCS policy that includes such an incentive will influence the usage of other biomass types from the cost and resource efficiency perspectives. If this is not done, the BECCS policy could result in reduced biomass availability for other purposes, such as long-lived biomass products and increased forest cutting. It seems most likely that it will not be sustainable to use higher-quality and more expensive forest products, such as sawed timber, for BECCS.

An additional potential side-effect is that some actors (forest owners) may argue that if the state or a company pays for BECCS, such an incentive should, for cost-efficiency reasons, also include other policy measures that remove carbon from the atmosphere, i.e., there should be a CDR policy rather than a BECCS policy. This could, for instance, be large-scale production of biochar (charring biomass and burying it). The forest industry may also claim that the net carbon uptake by the forests should also be

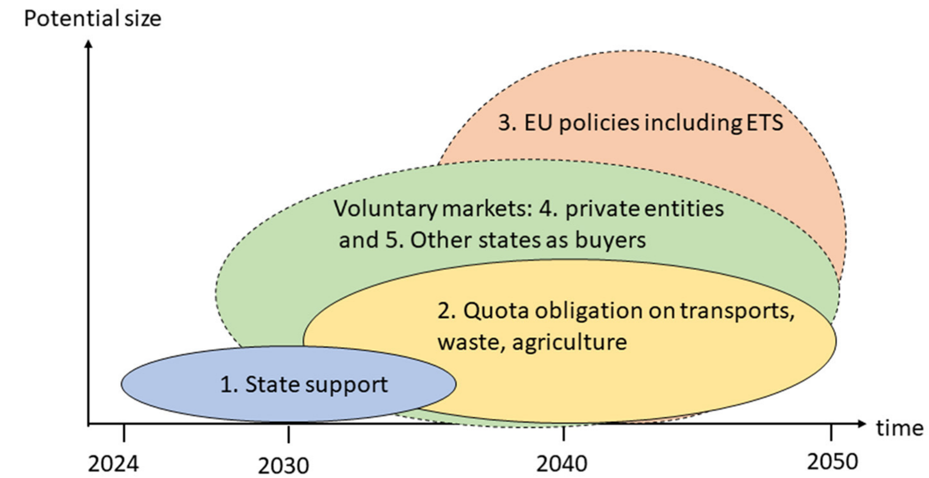

FIGURE 1 | Schematic illustration of the timing and potential volumes of the five Policy Models. The dotted lines correspond to markets that are not under the control of the Swedish state. As for the State support model (Model 1), there is a target of 1.8 Mt BECCS in Year 2030 (SOU2020:4 proposes to evaluate Model 1 in Year 2030, with no proposal as to what will happen after Year 2030); for Model 2, we assume that in the transport sector, from Year 2030 a quota obligation (for example, 10%) is imposed on fossil fuel use. The quota obligation increases steadily to reach 100% in Year 2045, to compensate for reduced emissions. In the waste and agricultural sectors, we assume that a quota obligation is also introduced, possibly later than that for the transport sector; and in Model 3, we assume that BECCS credits can be used in the EU emissions trading system from Year 2035 and onwards, although the demand for Swedish BECCS is uncertain. While voluntary markets (Model 4) and state buyers (Model 5) could create significant demand, this is difficult to assess in terms of volumes and timing.

subject to economic compensation. As part of routine forest management, thinning is performed two or three times during the forest life cycle to improve growth and provide feedstock for pulp and paper production. Typically, 25–30-year-old trees are cut down for these purposes (Swedish Forest Agency, 2008). If state or private companies would pay forest owners for producing biochar, they might use pulp wood for this purpose, which might result in a shortage of pulp wood, increased prices for paper and board, and reduced export revenues for Sweden. This calls for a policy package analysis that considers the expected values for different biomass products and feedstocks from the resource and cost-efficiency perspectives. This should also be important for gaining public acceptance for BECCS. Assigning a high price, in the vicinity of 100 € per ton, to stored biogenic carbon might release a powerful financial impetus to trigger actions that we cannot fully predict at the present time. Society needs to be cautious not to be caught up in a *Tyranny* of *Small Steps* behavior, where each incremental step is logical but where the eventual result is not what was intended in the first place. Thus, it should also be important that a BECCS policy be integrated with an overall policy for biomass, to avoid unwanted side-effects.

There should be a balance between the cost of emitting fossil carbon and the reward for providing negative emissions (Fuss and Johnsson, 2021). Thus, it is reasonable to propose that the incentive for implementing capture of fossil fuel emissions should be as strong as that for installing BECCS. Accordingly, in a situation for which a governmental policy for negative emissions is sufficiently strong to trigger negative emissions, say around 100 €/tCO_2, it would be problematic if the penalty (e.g., in the form of EU ETS) for emitting fossil CO_2 was considerably less-severe. This would result in an inefficient climate policy. Yet, a country such as Sweden with favorable conditions for BECCS may choose to incentivize the implementation and commercialization of BECCS over CCS in an initial phase, if it is regarded as contributing to technological developments of importance for the country and for the attainment of ambitious global climate targets.

Minx et al. (2018) have noted that a growing trend in the literature is drawing attention to the importance of understanding the difference between the technical potentials for CDR and their practical feasibility. Lenzi et al. (2018) have argued that uncertainties surrounding the potential side-effects of CDR at vast scales raises the question as to whether lower temperatures are obviously ethically preferable ("Keeping within 1.5°C could cause side-effects that are as bad as those in a world that is 2°C warmer," p. 304). They suggest that ethicists and social scientists should be more deeply involved in the elaboration of mitigation scenarios, in order to broaden the range of considerations included. On the other hand, it can be argued that a 2°C warming scenario will most likely require CDR to compensate for residual emissions in hard-to-abate sectors, as well as to compensate for an overshoot in emissions. Thus, the topic of the present paper—to discuss how negative emissions and BECCS in particular can be incentivized—should be of high importance, although there is an obvious need for further assessments of CDR and BECCS policies and how these can be part of a complete climate policy package.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary materials, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

The original work on incentives and financing was led by LZ in collaboration with KM. In preparation of this paper, FJ added sections on BECCS technologies and potentially adverse effects of BECCS policies and provided new insights to previous work. The manuscript has been discussed and improved by all authors, including writing, reviewing, adding references, and in other ways improving the paper.

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REFERENCES

Allen, M., Axelsson, K., Caldecott, B., Hale, T., Hepburn, C., Hickey, C., et al. (2020). *The Oxford Principles for Net Zero Aligned Carbon Offsetting*. Smith School of Enterprise and the Environment, Oxford University.

Anderson, K., and Peters, G. (2016). The trouble with negative emissions. *Science* 354, 182–183. doi: 10.1126/science.aah4567

Anthonsen, K. L., Aagaard, P., Bergmo, P. E. S., Erlström, M., Fareide, J. I., Gislason, S. R., et al. (2013), CO_2 storage potential in the Nordic region. *Energy Proc.* 37, 5080–5092. doi: 10.1016/j.egypro.2013.06.421

Asian Development Bank (2018). *Article 6 of the Paris Agreement*. Manila: Asian Development Bank. doi: 10.22617/TIM189647-2

Bednar, J., Obersteiner, M., and Wagner, F. (2019). On the financial viability of negative emissions. *Nat. Commun*. 10:1783. doi: 10.1038/s41467-019-09782-x

Bellamy, R., Fridahl, M., Lezaun, J., Palmer, J., Rodriguez, E., Lefvert, A., et al. (2021). Incentivising bioenergy with carbon capture and storage (BECCS) responsibly: comparing stakeholder policy preferences in the United Kingdom and Sweden. *Environ. Sci. Policy* 16, 47–55. doi: 10.1016/j.envsci.2020.09.022

Bellamy, R., and Geden, O. (2019). Govern CO_2 removal from the ground up. *Nat. Geosci*. 12, 874–876. doi: 10.1038/s41561-019-0475-7

Bellamy, R., Lezaun, J., and Palmer, J. (2019). Perceptions of bioenergy with carbon capture and storage in different policy scenarios. *Nat. Commun.* (2019) 10:743. doi: 10.1038/s41467-019-08592-5

Bui, M., Adjiman, C., Bardow, A., Anthony, E., Boston, A., Brown, S., et al. (2018). Carbon capture and storage (CCS): the way forward. *Energy Environ. Sci*. 11, 1062–1176. doi: 10.1039/C7EE02342A

Cox, E., Spence, E., and Pidgeon, N. (2020) Public perceptions of carbon dioxide removal in the United, States and the United Kingdom. *Nat. Clim. Change* 10, 744–749. doi: 10.1038/s41558-020-0823-z

Donofrio, S., Maguire, P., Zwick, S., and Merry, W. (2020). *Voluntary Carbon and the Post-Pandemic Recovery*. Washington DC: Ecosystem Marketplace.

Elkerbout, M., and Zetterberg, L. (2020). *EU ETS - Reform Needs in the Light of National Policies*. book for European Liberal Forum. Available online at: fores.se. (accessed August 9, 2021).

Equinor (2020). Northern Lights - A European CO_2 *Transport* and *Storage Network*. presentation by Per Sandberg.

European Commission (2003). *Directive 2003/87/EC of the European Union and of the Council of 13 October 2009 Establishing a Scheme for Greenhouse Gas Emission Allowance Trading Within the Community and Amending Council Directive 96/61/EC*.

European Commission (2013). Decision No 529/2013/EU of the European Parliament and of the Council of 21 May 2013 on *Accounting Rules* on *Greenhouse Gas Emissions* and *Removals Resulting From Activities Relating* to *Land Use, Land-Use Change and Forestry and on Information Concerning Actions Relating to Those Activities*.

European Commission (2018). *In-Depth Analysis* in *Support* of the *Commission Communication* COM (2018) 773 - A Clean Planet for *All. A European Strategic Long-Term Vision for a Prosperous, Modern, Competitive and Climate Neutral Economy*.

European Council (2019). *EUCO 29/19 Note from General Secretariat of the Council to Delegations on European Council Meeting 12 December 2019 - Conclusions*.

European Energy Exchange (2021). *Spot price on EUA:s*. Available online at: https://www.eex.com/en/market-data/environmental-markets/spot-market (accessed June 28, 2021).

Forster, J., Vaughan, N. E., Gough, C., Lorenzoni, I., and Chilvers, J. (2020). Mapping feasibilities of greenhouse gas removal: key issues, gaps and opening up assessments. *Glob. Environ. Chang*. 63:102073. doi: 10.1016/j.gloenvcha.2020.102073

Fridahl, M. (2017). Socio-political prioritization of bioenergy with carbon capture and storage. *Energy Policy* 104, 89–99. doi: 10.1016/j.enpol.2017.01.050

Fridahl, M., Bellamy, R., Hansson, A., and Haikola, S. (2020). Mapping multi-level policy incentives for bioenergy with carbon capture and storage in Sweden. *Front. Clim*. 2:604787. doi: 10.3389/fclim.2020.604787

Fridahl, M., and Lundberg, L. (2021). Actor Preferences in the *Design* of a *Support Scheme* for *Bioenergy* with *Carbon Capture* and *Storage* (BECCS). *(Aktörspreferenser i Design av ett Stödsystem för bio-CCS)*. In Swedish.

Fuhrman, J., McJeon, H., Doney, S. C., Shobe, W., and Clarens, A. F. (2019). From zero to hero?: why integrated assessment modeling of negative emissions technologies is hard and how we can do better. *Front. Clim*. 1:11. doi: 10.3389/fclim.2019.00011

Fuss, S., and Johnsson, F. (2021). The BECCS implementation gap-a Swedish case study. *Front. Energy Res*. 8:553400. doi: 10.3389/fenrg.2020.553400

Gambhir, A., Butnar, I., Li, P. H., Smith, P., and Strachan, N. (2019). A review of criticisms of integrated assessment models and proposed approaches to address these, through the lens of BECCs. *Energies* 12, 1–21. doi: 10.3390/en12091747

Geden, O., and Schenuit, F. (2020). *Unconventional Mitigation - CDR as a New Approach in EU Climate Policy*. Berlin: German institute for International and Security Affairs.

Global CCS Institute (2020). *Global Status of CCS 2020, the Global CCS Institute*. available online at: https://www.globalccsinstitute.com/ (accessed August 9, 2021).

Gnann, T., Plötz, P., Wietschel, M., and Kühn, A. (2017). "What is the best alternative drive train for heavy road transport?," *EVS 2017 - 30th International Electric Vehicle Symposium and Exhibition* (Stuttgart).

Gough, C., and Mander, S. (2019). Beyond social acceptability: applying lessons from CCS social science to support deployment of BECCS. *Curr. Sustain. Energy Reports* 6, 116–123. doi: 10.1007/s40518-019-00137-0

Gray, N., McDonagh, S., O'Shea, R., Smyth, B., and Murphy, J. D. (2021). Decarbonising ships, planes and trucks: an analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors. *Adv. Appl. Energy* 1:100008. doi: 10.1016/j.adapen.2021.100008

Hamrick, K., and Gallant, M. (2017). *Unlocking Potential - State of the Voluntary Carbon Markets 2017*. Washington, DC: Forest Trends' Ecosystem Marketplace. Available online at: https://www.cbd.int/financial/2017docs/carbonmarket2017.pdf (accessed May 22, 2019).

Hermwille, L. and Kreibich, N. (2016). *Identity Crisis? - Voluntary Carbon Crediting and the Paris Agreement. Report No. 02/2016*. Wupperthal: Wupperthal Institute for Climate, Environment and Energy.

Honegger, M., Poralla, M., Michaelowa, A., and Ahonen, H. (2021). Who is paying for carbon dioxide removal? Designing policy instruments for mobilizing negative emissions technologies. *Front. Clim.* 3:672996. doi: 10.3389/fclim.2021.672996

Honegger, M., and Reiner, D. (2018). The political economy of negative emissions technologies: consequences for international policy design. *Clim. Policy*. 18, 306–321. doi: 10.1080/14693062.2017.1413322

Horvath, S., Fasihi, M., and Breer, C. (2018). Techno-economic analysis of a decarbonized shipping sector: technology suggestions for a fleet in 2030 and 2040. *Energy Convers. Manag.* 164, 230–241. doi: 10.1016/j.enconman.2018.02.098

Hyams, K., and Fawcett, T. (2013). The ethics of carbon offsetting. *WIREs Clim. Change* 4, 91–98. doi: 10.1002/wcc.207

IEAGHG (2016). *Review of GHG Accounting Rules for CCS. 2016/TR3.*

Intergovernmental Panel on Climate Change (IPCC). (2018). *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)].

IOGP (2019). "The potential for CCS and CCU in Europe," *Report to the Thirty-Second Meeting of the European Gas Regulatory Forum 5–6 June, 2019* (Madraid: International Association of Oil and Gas Producers).

Johnsson, F., Normann, F., Svensson, E. (2020). Marginal abatement cost curve of industrial CO_2 capture and storage - a swedish case study. *Front. Energy Res.* 8:175. doi: 10.3389/fenrg.2020.00175

Kamb, A., and Larsson, J. (2018). *Klimatpåverkan Från Svenska Befolkningens Flygresor 1990-2017*. Chalmers Tekniska Högskola, Avdelningen för Fysisk Resursteori.

Karlsson, H., Delahaye, T., Johnsson, F., Kjärstad, J., and Rootzén, J. (2017). Immediate deployment opportunities for negative emissions with Bio-CCS: a Swedish case study. *arXiv Preprint.* arXiv:1705.07894.

Keith, D. W., and Rhodes, J. S. (2002). Bury, burn or both: a two-for-one deal on biomass carbon and energy - Reply. *Clim. Change*. 54, 375–377. doi: 10.1023/A:1016187420442

Laude, A. (2020). Bioenergy with carbon capture and storage: are short-term issues set aside? *Mitig. Adapt. Strateg. Glob. Chang.* 25, 185–203. doi: 10.1007/s11027-019-09856-7

Lebling, K., McQueen, N., Pisciotta, M., and Wilcox, J. (2021). *Direct Air Capture: Resource Considerations and Costs for Removal*. World Resources Institute.

Lenzi, D., Lamb, W., and Hilaire, J. (2018). Weigh the ethics of plans to mop up carbon dioxide. *Nature* 561, 303–305. doi: 10.1038/d41586-018-06695-5

Leonard, K. (2009). *Quality Enhancement in Voluntary Carbon Markets: Opening up for Mainstream*. Hamburg: Diploma Verlag.

McLaren, D., Tyfield, D., Willis, R., Szerszynski, B., and Markusson, N. (2019). Beyond "Net-Zero": a case for separate targets for emissions reduction and negative emissions. *Fron. Clim.* 1:4. doi: 10.3389/fclim.2019.00004

Minx, J., Lamb, W., Callaghan, M., Fuss, S., Hilaire, J., Creutzig, F., et al. (2018). Negative emissions part 1: - research landscape and synthesis. *Env. Res. Lett.* 13:063001. doi: 10.1088/1748-9326/aabf9b

Möllersten, K., and Yan, J. (2001). Economic evaluation of biomass-based energy systems with CO_2 capture and sequestration in kraft pulp mills - the influence of the price of CO_2 emission quota. *World Resour. Rev.* 13, 509–525. Available online at: https://www.researchgate.net/publication/270893240_Economic_evaluation_of_biomass-based_energy_systems_with_CO2_capture_and_sequestration_in_kraft_pulp_mills_-_The_influence_of_the_price_of_CO2_emission_quota (accessed August 9, 2021).

Möllersten, K., Yan, J., and Moreira, J. R. (2003). Potential market niches for biomass energy with CO_2 capture and storage - opportunities for energy supply with negative CO_2 emissions. *Biomass Bioenerg.* 25, 273–285. doi: 10.1016/S0961-9534(03)00013-8

Möllersten, K., Zetterberg, L., Torvanger, A., Siikavirta, H., and Kujanpää, L. (2021). *Policies for the Promotion of BECCS in the Nordic Countries*. Nordic Council of Ministers.

Nordic Council of Ministers (2016). *Sustainable Jet Fuel for Aviation - Nordic Perspectives on the Use of Advanced Sustainable Jet Fuel for Aviation*. Report TemaNord 2016:538. Available online at: https://www.nordicenergy.org

Obersteiner, M., Azar, C., Kauppi, P., Möllersten, K., Moreira, J., Nilsson, S., et al. (2001). Managing climate risk. *Science* 294, 786–787. doi: 10.1126/science.294.5543.786b

Obersteiner, M., Bednar, J., Wagner, F., Gasser, T., Ciais, P., Forsell, N., et al. (2018). How to spend a dwindling greenhouse gas budget. *Nat. Clim. Chang.* 8, 2–12. doi: 10.1038/s41558-017-0045-1

Organisation for Economic Co-operation and Development (OECD) (2021). *Recommendation of the Council on Guiding Principles concerning International Economic Aspects of Environmental Policies*, OECD/LEGAL/0102.

Poralla, M., Honegger, M., Ahonen, H., and Michaelowa, A. (2021). *Sewage Treatment for the Skies: Mobilising Carbon Dioxide Removal Through Public Policies and Private Financing*. Freiburg: Perspectives Climate Research.

PuroEarth (2021). *Carbon Removal Methods*. Available online at: https://puro.earth/services/ (accessed June 28, 2021).

Rickels, W., Proel,β, A., Geden, O., Burhenne, J., and Fridahl, M. (2021). Integrating carbon dioxide removal into european emissions trading. *Front. Clim.* 3:690023. doi: 10.3389/fclim.2021.690023

Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V., et al. (2018). "Mitigation pathways compatible with 1.5°C in the context of sustainable development," In: *Global warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)].

Schneider, L., Kollmuss, A., and Lazarus, M. (2014). *Addressing the Risk of Double Counting Emission Reductions Under the UNFCCC*. Stockholm Environment Institute. doi: 10.1007/s10584-015-1398-y

Swedish Energy Agency (2021a). *Förslag på Utformning av ett System för Driftstöd, i Form av Omvänd Auktionering eller Fast Lagringspeng, för Avskiljning, Infångning och Lagring av Koldioxid Från Förnybara Källor (bio-CCS), dnr-2020-23877, April 15, 2021* (in Swedish).

Swedish Energy Agency (2021b). *The Electricity Certificate System*. Available online at: www.energimyndigheten.se/en/sustainability/the-electricity-certificate-system/ (accessed June 24, 2021).

Swedish EPA (2021). *Sweden's Territorial Emissions and Uptake of Greenhouse Gases*. Available online at: http://www.naturvardsverket.se/klimatutslapp (accessed March 19, 2021).

Swedish Forest Agency (2008). *Skogliga Konsekvensanalyser 2008 - SKA-VB 08*. Skogsstyrelsen Report 25-2008. In Swedish.

Swedish Government (2017). *Regeringens Proposition 2016/17:146 "Ett Klimatpolitiskt Ramverk för Sverige*" (in Swedish). Available online at: regeringen.se (accessed August 9, 2021).

Swedish Government (2020). *SOU 2020:4. Vägen till en Klimatpositiv Framtid - Betänkande av Klimatpolitiska Vägvalsutredningen, 2020*. Stockholm: Norstedts Juridik.

Tcvetkov, P., Cherepovitsyn, A., and Fedoseev, S. (2019). Public perception of carbon capture and storage: a state-of-the-art overview. *Heliyon* 5:e02845. doi: 10.1016/j.heliyon.2019.e02845

Thunman, H., Berdugo Vilches, T., Seemann, M., Maric, J., Cañete Vela, I., Pissot, S., et al. (2019). Circular use of plastics-transformation of existing petrochemical clusters into thermochemical recycling plants with 100% plastics recovery. *Sustain. Mater. Technol.* 22:e00124. doi: 10.1016/j.susmat.2019.e00124

United Nations Framework Convention on Climate Change (UNFCCC) (2015). *The Paris Agreement*. Available online at: https://unfccc.int/process-andmeetings/ the-paris-agreement/the-paris-agreement (accessed June 24, 2021).

Williams, R. (1998). "Fuel decarbonisation for fuel cell applications and sequestration of the separated CO_2," in *Eco-Restructuring: Implications for*

Sustainable Development, ed R. Ayres (Tokyo, New York, NY: United Nations University Press), 180–222.

Wolske, K. S., Raimi, K. T., Campbell-Arvai, V., and Hart, P. S. (2019). Public support for carbon dioxide removal strategies: the role of tampering with nature perceptions. *Clim. Change* 152, 345–361. doi: 10.1007/s10584-019-02375-z

Zetterberg, L., Källmark, L., and Möllersten, K. (2019). *Incentives and Financing of Bio-CCS in Sweden (Incitament och Finansiering av Bio-CCS i Sverige).* IVL Report C417. Stockholm: IVL Swedish Environmental Research Institute (In Swedish).

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