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Original research article

FinanceForFuture: Enforcing a CO_2 emitter liability using atmospheric CO_2 removal deposits (ACORDs) to finance future negative emissions

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ABSTRACT

The gigantic volumes of carbon dioxide (CO_2) removal likely needed to comply with the Paris Agreement beg the question of who should pay for the negative emissions. Incentivizing negative emissions is difficult, as it entails reversing the fiscal attractiveness associated with carbon taxes and emissions trading in favour of the more unattractive need to pay for removals. The inherent difficulty of funding global public goods associated with large private costs will make it hard for future governments to share this burden among themselves. We propose that this problem can be solved by a CO_2 emitter liability operationalized through Atmospheric CO_2 Removal Deposits (ACORDs). Anyone that emits fossil CO_2 to the atmosphere would be obliged to finance the removal of at least as much CO_2 from the atmosphere. Linking the liability to ACORDs acknowledges that a major part of the negative emissions needs to be made in the future. The emitters' financial deposits, including earnings, can be redeemed upon certified proof of removal. The ACORDs system would comply with the widely accepted principle of producer liability, i.e., that companies are responsible for the damage caused by their products. The system would also provide additional incentives to reduce emissions and an innovative funding source for coming generations to accomplish negative emissions. Furthermore, inequity and historical emissions can be addressed by gradually increasing overcompensation. The paper also includes a critical assessment of the basis of negative emissions, i.e., the need, the technologies and their potentials, the costs, and the required retention time.

1. Introduction

The carbon budget for 1.5 °C is likely going to be exhausted around 2030, after which achieving the 1.5 °C goal hinges on offsetting all future carbon dioxide (CO_2) emissions through negative emissions while creating headroom for hard-to-abate methane and nitrous oxide emissions. Consistently, all recent scenarios for meeting the 1.5 °C goal have been associated with large future negative emissions (see Fig. 1) [1]. Despite these massive amounts of projected negative emissions, the scenarios have not considered any realistic mechanism for financing negative emissions.

The fundamental question this work aims to answer is: What measures are needed to steer society towards a future that meets the 1.5 °C goal? Measures to incentivize the rapid emissions reductions needed are known and have been deployed to some extent, in contrast to measures needed to accomplish the negative emissions, which will be the focus of this paper.

Insufficient greenhouse gas emissions reductions will inevitably result in an overspending of the carbon budget, putting a large burden on our descendants to remove a huge quantity of CO_2 from the atmosphere. The required removal quantity obviously depends on the scale of the overspending but could be in the range 500–1000 $GtCO_2$ at a cost in the order of 10,000 US$/capita globally, assuming a cost of at least 100 US$/$tCO_2$.

Incentivizing emissions reductions by pricing CO_2 is attractive as it steers the market to the least costly ways of avoiding emissions and could provide fiscal income. Even so, emissions have been hard to price. Incentivizing negative emissions is fundamentally more difficult than pricing emissions. It lacks the fiscal attractiveness of carbon taxes or emissions trading systems, and in the case of the burden being left to our descendants, it is hard to identify entities with the liability to pay for negative emissions.

This has been characterized as an "incentive gap" [2] between scenarios and existing policy enablers, leading others to describe this lack of

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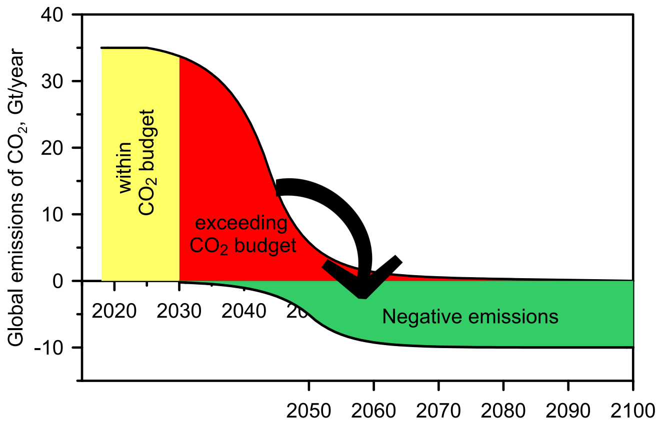

Fig. 1. Example of scenario in which emissions are halved by 2045 and the budget is exceeded by 510 Gt. The CO_2 budget for the maximum 1.5 °C target is exhausted around 2030, meaning that all emissions after that must be removed from the atmosphere by negative emissions.

policy incentives as resulting in an "implementation gap" [3] for specific CO_2 removal technologies in specific jurisdictions, resulting in industry giving low priority to removals [4], and to contest the modelled scenarios as "infeasible" [5].

The major moral hazard, or moral collapse, does not only involve handing over a gigantic climate debt to our children and grandchildren, but handing over a problem that is likely to be insoluble. The problem is primarily associated with sharing the burden between nation states with widely different historical emissions, as well as different opportunities for achieving negative emissions [6]. At the level of individual nation states, it is difficult to see how negative emissions – a global public good associated with large private costs and few tangible private benefits – can be prioritized by a sufficient number of governments in competition with material public expenditures such as healthcare and education [7].

We propose that this problem can be solved by a CO_2 emitter liability operationalized through Atmospheric CO_2 Removal Deposits (ACORDs). Anyone that emits fossil CO_2 to the atmosphere would be obliged to finance the removal of at least as much CO_2 from the atmosphere. Linking the liability to ACORDs acknowledges that a major part of the negative emissions needs to be made in the future. The emitters' financial deposits can be redeemed upon certified proof of removal. The financial deposits will be invested in mutual funds, which means that the value of the deposit deeds will rise with the cumulative revenue and the incentive for redeeming these will increase accordingly. We further suggest that deposit receipts can be traded. An ACORDs market could foster the growth of specialized removal brokers and removal operators, allowing for potential efficiency gains through reduced transaction costs and benefits of scale.

By complying with the widely accepted principle of producer liability, i.e., that companies are responsible for the damage caused by their products, our proposal for ACORDs could be judged fair, comprehensible, and rational. In addition, the costs imposed on emitters by operationalizing the liability would significantly strengthen any existing incentives for emissions reductions. With the carbon budget for 1.5 °C soon being exhausted, such a liability should be introduced as soon as possible in order to minimize temperature overshoot and associated loss and damage, as well as the risk of triggering climate system tipping points.

The ACORDs are a complement to, and dependent on, other policy measures, such as the European Union's Emissions Trading System (EU ETS), to reduce fossil CO_2 emissions as quickly as possible. It is vital that ACORDs not be used as an excuse for delaying the needed reduction of fossil CO_2 emissions.

Existing and proposed schemes for financing negative emissions are reviewed in Section 2. The need for and the particular challenge of incentivizing negative emissions are discussed in Section 3. The rationale and possible construction of ACORDs, further exemplified through application to the European Union, are investigated in Sections 4 and 5. The following questions relevant to the realism and implementation of ACORDs will also be addressed in the following sections:

6) How are ACORDs combined with other incentives, which risks could the ACORDs be exposed to and how can these risks be managed?

7) What is the potential, cost, and development status of available methods for negative emissions?

8) Are the costs related to ACORDs reasonable?

9) What is the potential impact on ACORDs of CO_2 leakage from carbon storage?

10) How can ACORDs with overcompensation be used to address inequity and historical emissions, buffers for storage-related uncertainties, and needs for increasingly stronger disincentives for fossil CO_2 emissions? Could or should ACORDs be complemented with tools that steer towards or away from certain methods of negative emissions?

1.1. *Methodological approach*

This paper applies an unorthodox methodology to gradually build an argument for ACORDs. In doing so, we iteratively engage with previous literature on the technical potential for, cost of, and existing and prospective policy incentive structures for CO_2 removals, both to derive key questions and to explore answers. The iterative exchange with previous literature allows us to identify key questions concerning the financing of CO_2 removals, which allows us to elaborate building blocks to gradually introduce our proposed answer to the CO_2 removal incentivization gap, i.e., ACORDs.

This approach to building an argumentative paper is combined with several distinct methods to calculate potential effects and illustrate costs and revenue streams associated with ACORDs. These methods are introduced throughout the paper with sufficient transparency to permit reproduction and scrutiny. The gradual introduction of calculation methods involves clearly outlining assumptions regarding input parameters (e.g., cost estimates and discount rates) and spelling out the equations used to calculate various key parameters underpinning the logic of ACORDs.

2. Existing or proposed schemes for funding negative emissions

The need to finance CO_2 removals is widely acknowledged as a necessary supplement to scaling up emissions reductions. The incentive gap for CO_2 removal is obvious for all removal methods, but most acute for methods associated with increasing production costs but no revenue streams. Examples of such removal methods include Bioenergy with Carbon Capture and Storage (bio-CCS) [7] and Direct Air Carbon Capture and Storage (DACCS) [8].

Several funding mechanisms for negative emissions are, however, already in force in different jurisdictions. In California, for example, the Low Carbon Fuel Standard incentivizes the gradual reduction of the carbon footprint of transportation fuels, which includes the option to compensate for fossil CO_2 emissions with negative emissions generated through DACCS [9].

In the USA, at the federal level, the government provides tax credits for CCS, including bio-CCS and DACCS. At present, the tax deduction for CCS and bio-CCS is 85 US$/t$CO_2$ permanently stored, 60 US$/t$CO_2$ when utilized in industry or for enhanced oil recovery, and 180/130 US $/t$CO_2$ for DACCS [10].

In Sweden, negative emissions using bio-CCS will be bought by the Swedish state by reversed auctions, starting in 2023 [11]. Although not all auction design details are official at the time of writing, state aid will cover the costs of capture, transport, and storage for a likely period of 15 years. The support involves 3 bn€ and the Swedish Energy Agency is authorized to issue contracts worth 150 M€/y [12].

Several additional jurisdictions provide economic incentives for carbon removal. Noteworthy examples are the New Zealand Emissions Trading System, which includes forest carbon, and the Australian Emissions Reductions Fund, which incentivizes soil carbon sequestration in agriculture [13]. Carbon removal incentives are also considered in other jurisdictions, such as in the UK, Ireland, Luxembourg, New York State, and elsewhere [14].

The European Union is also actively considering incentivizing removals beyond existing regulations that primarily target the forestry sector. The EU ETS does not include negative emissions at present. However, the European Commission acknowledges the future need to use negative emissions to compensate for hard-to-abate residual emissions [15]. Rickels et al. [16] explored design options that would allow for the inclusion of negative emissions in the EU ETS, and proposed to establish an institution – a Carbon Central Bank – mandated to procure and stock removal credits and act as a clearinghouse between the removals and the EU ETS market, using removal credits in the future to stabilize the EU ETS price signal [17].

Myles et al. [18,19] proposed a mandatory link between fossil fuel extraction and carbon sequestration; the extraction of fossil fuels would then be obliged to pay for CCS of a gradually increasing fraction of the carbon extracted, reaching 100 % when the carbon budget is exhausted. The purpose of the proposed certificate scheme is clearly to support CCS of fossil CO_2.

Later, Lyngfelt proposed a similar scheme [20], but aimed solely at financing negative emissions. The reasoning behind focusing on financing negative emissions is that, unlike removals, reductions of fossil CO_2 emissions, including the use of CCS, are already incentivized through existing and planned CO_2 taxes or cap-and-trade. In 2021 Myles et al.'s ideas resurfaced under the brand Carbon Takeback Obligations, which would support fossil CCS as well as a gradually increasing fraction of negative emissions with DACCS and bio-CCS [21,22]. Here the possibility of eventually going below net zero could be incentivized by overcompensation, i.e., requiring the takeback of CO_2 to be more than 100 % [22].

A problem with the various forms of takebacks discussed is that they will be made more or less at the same time as the fossil carbon is extracted. With the exception of the mentioned proposal for overcompensation, the need to go below net zero is not addressed. It is not evident that such overcompensation could be a sufficient tool to address the large negative emissions needed in the latter part of the century. Moreover, the above schemes do not solve the problem of future burden-sharing of the climate debt imposed on coming generations.

Expert opinions on policies for incentivizing bio-CCS were investigated in a study that reflects the discourse on incentives [23]. Five options were considered:

i) subsidy,
ii) integration in a cap-and-trade system,
iii) carbon tax combined with a refund scheme, which involves extending the carbon tax to biogenic CO_2,
iv) quota obligation, and
v) reverse auctioning.

Here, options i) and v) assume public funding, whereas options ii), iii), and iv) do not address the need to finance future negative emissions.

A few studies have addressed the temporal dislocation of emissions reductions and the need for future removals. Bednar et al. [24] discussed the possibility of saving carbon tax revenues in funds for financing future negative emissions. They concluded that it would be extremely challenging to protect these funds from diversion for other purposes, for example, due to political changes or stressed public finances. Instead, they introduced a concept of carbon debts called Carbon Removal Obligations. The idea is that these debts would be treated similarly to financial debts, being issued by managing authorities (e.g., central banks) to commercial banks at a base rate. Commercial banks would subsequently issue these debts to emitters, and the commercial banks would be held liable in case of insolvent debtors. Reinsurance of this liability comes with a cost, which further increases the interest that debtors need to pay to the banks.

Lemoine [25] proposed that the emitter should post a bond, i.e., a direct payment for the worst-case social cost of carbon. In return the emitter receives a “share”, initially of the same value. At regular intervals, the regulator pays a dividend to the emitter, which is deducted from the share. Also, the damage associated with the “share” during the period is deducted. The owner receives the remaining value of the share when removing the associated amount of CO_2 from the atmosphere. The calculation of the cumulative worst-case social costs associated with CO_2 affecting the climate for hundreds of years is not trivial and there is a risk that the cost could be insurmountable. The proposal would give a strong incentive for immediate negative emissions, but if immediate negative emissions are limited, the share could lose its value before any CO_2 is removed, depending on deductions and initial value.

Rickels et al. [17] proposed another solution, namely, to mandate a central authority to start procuring carbon removal today to, if need be, supply the EU ETS market in the future. One of the underlying arguments of Rickels et al. is that removal activities need to be incentivized at the earliest convenience, while the premature introduction of removal credits on the EU ETS market would undermine incentives to reduce emissions.

Our proposal for ACORDs instead acknowledges that there is also a need to raise funding for future removal opportunities, with a technical potential that is yet to materialize. Building such removal capacity will take time and the deposit receipts would generate a source of immediate as well as long-term stable financing that, unlike finance allocated to a fund, is not prone to diversion.

3. Carbon budgets and need for negative emissions

The concept of a carbon budget denotes the global amount of cumulative net CO_2 emissions that are compatible with meeting a specific climate stabilization target with a specified probability [26]. The carbon budgets for 1.5 °C and 2 °C are specified in ranges [27,28] due to uncertainties but also due to assumptions such as future emissions of other greenhouse gases, feedback mechanisms, and the accepted risk (e.g., 33 % or 50 %) of not meeting the target.

Recent estimations of the remaining carbon budgets for restricting the warming to 1.5 °C or 2 °C correspond to about 400 and 1150 $GtCO_2$, respectively, from 2020 onwards and with a risk of less than 33 % of not meeting the targets [26]. These budgets also assume that other greenhouse gases are significantly reduced.

The global fossil CO_2 emissions were, on average, 36 $GtCO_2$/y in the 2018–2020 period [29], and preliminary data as of March 2022 indicate 36.4 $GtCO_2$/y for 2021 [30]. The United Nations Framework Convention on Climate Change (UNFCCC) estimates that full implementation of nationally determined contributions (NDCs) to the Paris Agreement would result in emissions being 1.6 % higher in 2025 and 0.3 % lower in 2030, compared with 2019 levels (excluding net emissions from land-use and forestry) [31]. Note that the UNFCCC numbers are for all greenhouse gases but can be assumed to give an indication also of actual CO_2 emissions. Using these estimated increases and interpolation, the data indicate that the CO_2 budget for a 67 % chance of meeting the 1.5 °C goal will be spent in 2030.

It would be possible to delay the point in time when the budget is spent through rapid worldwide emissions reductions. However, even if appropriate incentives were to be put in place, inertia in the energy system (e.g., technology roll-out pace) would delay the emissions reduction rate. Furthermore, a large part of the CO_2 emissions originate in countries that still have moderate ambitions with respect to climate mitigation.

Thus, there is little doubt that negative emissions are needed to meet stringent climate targets. Fig. 1 illustrates the scope of the challenge: if emissions are halved in 2045, we would need around 10 $GtCO_2$/y of

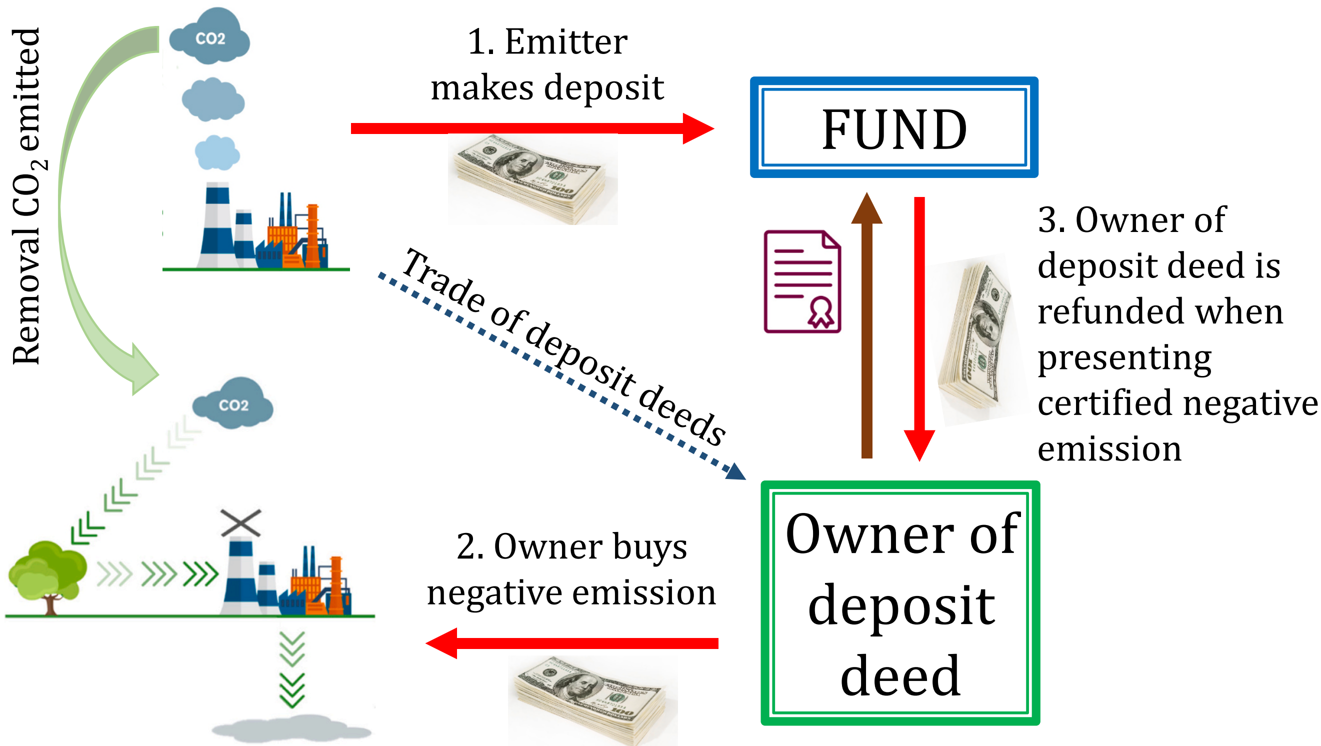

Fig. 2. Using Atmospheric CO_2 Removal Deposit deeds to secure the liability of emitters to take back emissions.

negative emissions in the second half of this century. The figure also illustrates the intertemporal dilemma of making the CO_2 emitters responsible for removing their emissions. Delays between emissions and removals underlines the moral hazard of leaving our grandchildren with this climate debt, which involves not only the duty to accomplish such negative emissions but also with the much greater challenge of finding, agreeing on, and implementing a model for sharing this burden between and within nations.

For a more than 50 % probability of stabilizing the temperature at 1.5 °C by 2100 with limited or no temperature overshoot, 97 different scenarios have been investigated in the 6th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). All of these scenarios use negative emissions to meet the greenhouse gas budget target. In fact, the CO_2 emissions turn net-negative in all 97 scenarios before the end of the century, with the median scenario reaching net-zero CO_2 slightly after 2050. In the 133 scenarios with a high temperature overshoot and more than 50 % probability of stabilizing the temperature at 1.5 °C by 2100, the dependence on negative emissions increases [32].

While negative emissions have come to play an increasingly significant role in emission scenarios, there is also good reason to question their prominence [32]. An obvious argument against negative emissions is that it is better to avoid bringing fossil carbon into circulation than to pay hefty sums for its permanent removal. Another argument is that introducing this backdoor escape may distract us from enforcing rapid emissions reductions, leaving an even greater burden to coming generations.

Whether our failure to reduce CO_2 emissions in time can be blamed on the promise of future negative emissions, or whether, conversely, the adoption of the more stringent climate targets of the Paris Agreement was helped by the prospect of possible negative emissions, is not clear. Nevertheless, there is obviously a risk that needed emissions reductions are being delayed by the promise of negative emissions, as well as a risk that the fear of the backdoor of negative emissions could delay or hinder the needed incentives to employ negative emissions.

3.1. *The inherent difficulty in incentivizing negative emissions*

Even though it is still poorly implemented, it should be simple to incentivize emissions reductions, for example, through taxation or cap-and-trade systems. Both a tax and the auctioning of emissions allowances in cap-and-trade systems generate fiscal incomes. The possibility to provide an incentive for reduced emissions and at the same time generate fiscal income ought to be attractive to governments. Still, although a growing number of countries are introducing carbon pricing mechanisms, there is a long way to go before they provide sufficient incentives for the rapid emissions reductions needed.

Incentivizing negative emissions is fundamentally more difficult. Here, the attractiveness of generating income and spurring emissions reductions is reversed in favour of the more unattractive need to pay for carbon removal. To achieve the large scale of negative emissions needed in order to meet climate goals, it is necessary to find someone who is willing to pay, or rather, who could be made to pay for negative emissions. While it is difficult enough to agree on when, where, and how CO_2 emissions should be reduced, the issue of sharing the burden of removing CO_2 from the atmosphere is even more complicated. Firstly, the large differences in historical emissions as well as other differences such as GDP per capita would likely make it very difficult for nation states to agree on how to share responsibility for CO_2 removal. Secondly, possibilities for biomass production and CO_2 storage vary considerably between regions, which means that the financing of negative emissions must be transferred between countries.

So, how could the cost of amortizing this gigantic debt be shared between nation states? And would it be possible to make essentially all future ministers of finance willing to have their taxpayers pay their share of this debt, especially considering the potential need to transfer money to other countries? In one scenario, the cost to industrialized countries could peak at 15 % of GDP [33]. It is easy to imagine the difficulties of dedicating such amounts of public funding, in competition with healthcare, social welfare, education, and other prioritized expenditures. Clearly, to assume that taxpayers will pay for this is unrealistic, which means that a more reliable and sustainable mechanism for paying

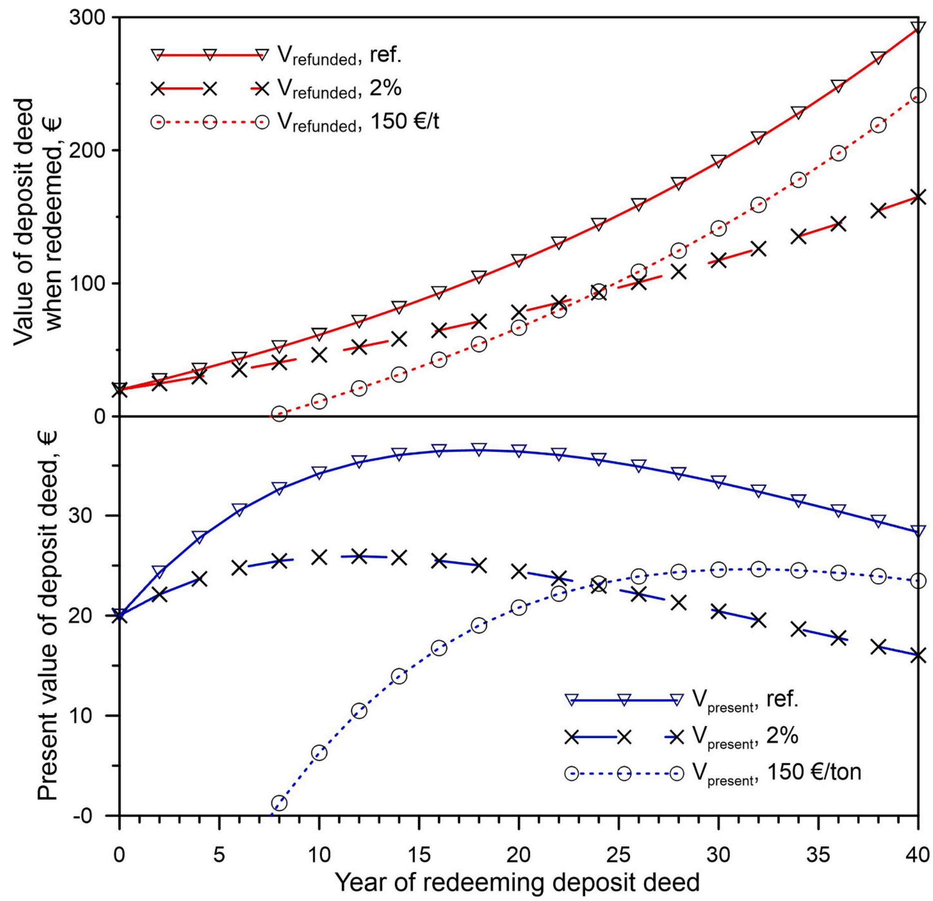

Fig. 3. Value of deposit deeds versus year of redemption. Upper panel: value when refunded. Lower panel: present value.

the costs of negative emissions is needed.

4. A rational solution for meeting the 1.5 °C carbon budget

The carbon budget for the 1.5 °C goal will be exhausted within a few years, and when the budget is spent every future tonne of CO_2 emitted will need to be removed from the atmosphere using negative emission technologies. It is obviously not a good idea to emit CO_2 at low or no cost, and then to remove it from the atmosphere at high cost. To meet the Paris Agreement's temperature objective, two elements are urgently needed:

- pricing fossil CO_2 emissions to direct market forces towards rapid and efficient emissions reductions; and
- sustainable financing of the atmospheric removal of CO_2.

These two needs can be combined in a rational solution, which is to make all polluters pay for the future removal of the CO_2 they emit, i.e., a CO_2 Emitter Liability. A likely price level would be of the order of 0.1–0.2 US$/kg$CO_2$, based on the estimated level of costs of several negative emission technologies [34].

There are several possibilities for organizing this. One possibility is that emitters pay for their emissions directly to a public fund that buys negative emissions, for example, via long-term contracts with operators of bio-CCS plants. However, a better solution could be to avoid giving public entities the responsibility for procuring negative emissions and instead regulate a market for removals. This could be organized with a system in which the emitters deposit money for the future negative emissions in a public fund, and reclaim the money when the negative emissions have been accomplished. This way of operationalizing the CO_2 Emitter Liability is here called Atmospheric CO_2 Removal Deposits (ACORDs).

5. Atmospheric CO_2 removal deposits (ACORDs)

The basic principle of ACORDs is that CO_2 emitters are liable for removing the CO_2 emitted and need to deposit guarantees to ensure that this removal will take place. Thus, the emitter will be burdened with the cost of the future removal, and therefore have a strong incentive to minimize CO_2 emissions.

The financing of future CO_2 removals will be secured by obliging emitters to buy deposits corresponding to their emissions. The deposits will be redeemed when an owner of a deposit receipt can demonstrate the certified removal of CO_2. Owners of deposit receipts can either implement removal themselves, with third party verification, or buy certified removals from external actors (Fig. 2). The owner of the deposit receipts can be expected to make long-term agreements with companies specializing in CO_2 removal, also securing investments in capital-intensive carbon removal. Furthermore, deposit receipts can be traded, establishing an ACORDs market that can lead to more efficient allocation of resources to develop and operate negative emission technologies.

The deposit obligations of emitters will be overseen by a public institution, and the money collected will be invested for good returns. The depositors will be credited with a major part of the returns, which means that the value of the deposit receipts will increase with time. The market value of a deposit will essentially be the cost of the deposit receipt issued plus returns minus the cost of CO_2 removal.

Assuming the emitter sells the deposit receipts, the effective cost, C_{eff}, of the emissions will be:

$$C_{eff} = C_{fee} - V_{market} \tag{3}$$

Table 1
Input data for three cases shown in Fig. 3.

	R	i	C_{fee}	$C_{negative\ emission}$	Symbol in Fig. 3	$year_{max}$
Reference case	3 %	6 %	120	100	▽	18
Low returns	2 %	6 %	120	100	○	12
High cost	3 %	6 %	120	150	✖	31

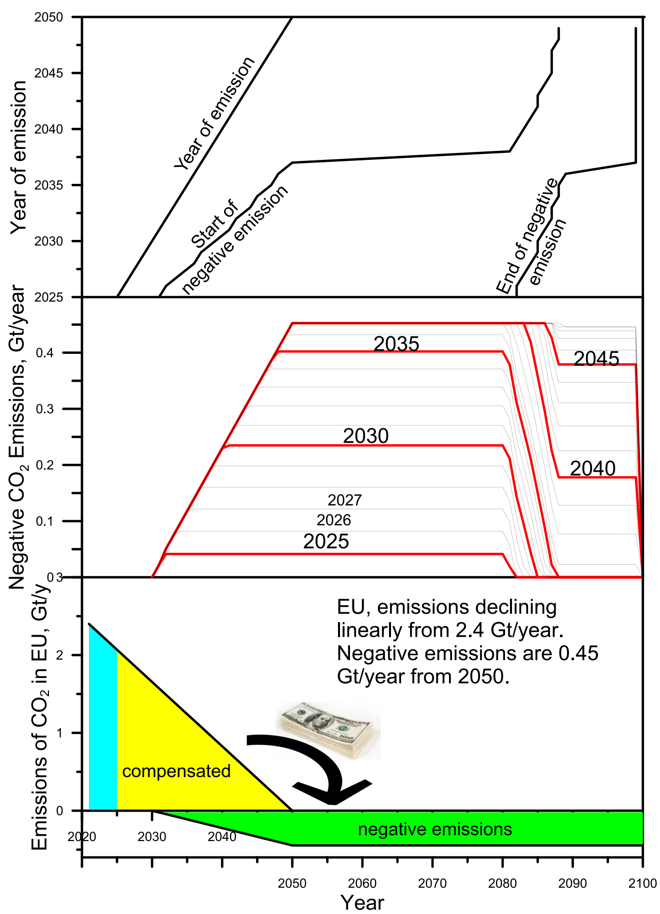

Fig. 4. An example showing assumed fossil CO_2 emissions the European Union, and how the emissions from 2025 and onwards can be recovered from the atmosphere by negative emissions. In this simplified scheme, it is assumed that emissions are reduced linearly until 2050.

where C_{fee} is the deposit made per tCO_2 and V_{market} is the market price of the deposit receipts. The market price when the emissions are made will be a function of the estimated future market price of the deposit receipts when they are refunded. The amount refunded, $C_{refunded}$, is the deposit plus accumulated revenue:

$$C_{refunded,n} = C_{fee}(1+r)^n \tag{4}$$

where r is the interest and n is the number of years. The market price when negative emissions have been effectuated and deposits are returned, $V_{refunded}$, should be:

$$V_{refunded,n} = C_{fee}(1+r)^n - C_{negative\ emission} \tag{5}$$

where $C_{negative\ emission}$ is the cost of buying negative emissions. Except for the exceptional case of negative discount rates, the present value, $V_{present}$, is lower than the future market price:

$$V_{present,n} = V_{refunded,n}\frac{1}{(1+i)^n} \tag{6}$$

where i is the discount rate used to calculate the present value. Thus, the present value of a deposit deed that is redeemed the n^{th} year is:

$$V_{present,n} = \left(C_{fee}(1+r)^n - C_{negative\ emission}\right)\frac{1}{(1+i)^n} \tag{7}$$

Fig. 3 shows how the market value of the deposit deeds when refunded as well as the present value depend on the year of redemption. Here a fixed monetary value is assumed. The reference case, Table 1, assumes a discount rate, i, of 6 %, an interest rate resulting from the revenues, r, of 3 %, a deposit fee, C_{fee}, of 120 US\$/tCO_2, and a price of negative emissions of 100 US\$/tCO_2. Because of revenues, the value of the deposits increases steadily with time, whereas the present value will go through a maximum because discount interest is higher than the interest earned from the revenues. For the case of lower revenues, $r = 2$ %, the rise in value is slower, and the maximum present value is reached earlier, i.e., after 12 years instead of 18 years for the reference case. For the third case, in which the cost of negative emissions is 150 US\$/t, i.e., higher than the fee, the value of the deposit deeds will not be sufficient to pay for negative emissions in the first years. Eventually the values of the deposit deeds will be higher than the cost, leading to both a positive value and a positive present value. The fees will likely not be redeemed before their worth is higher than the cost of negative emissions, so the actual present market value will correspond to the present value for a period of years after they have reached a positive value, i.e., the period when it can be assumed that the deposit deeds will be redeemed. This period of years would likely be associated with long-term contracts for CO_2 removals, which would provide safety for the large investments associated with, for example, bio-CCS. The following observations can be made:

1) Because of the returns, the value of the fees will sooner or later be positive, even if the initial fee is lower than the cost of negative emissions.
2) The present value of the deposit deeds will always be positive – that is, under the condition that there is no rule that forces redemption before the year that the amount that can be redeemed is higher than the cost of negative emissions.
3) Because of returns, r, being smaller than the discount rate, i, the present value of fees will always go through a maximum. When the maximum is passed, the value of the deposit deeds, $V_{refunded}$, will increase more slowly than the discount rate, which means that it is a disadvantage to further delay redemption. The optimal period of redemption will thus be centered around this maximum.
4) A fee that is lower than the actual cost of negative emissions may significantly delay the year of implementing the negative emissions. Therefore, it is important that the fees reflect the actual cost.

Although the returns will gradually increase the value of the deposits, owners of the deposits can be expected to have an interest in releasing the capital locked into them. Consequently, the market will have an incentive not to delay the redemption of the deposits. Furthermore, the development and demonstration of "first-of-its-kind" capture plants can be expected to be subject to subsidies that will alleviate the higher costs of early movers.

5.1. An example applying Atmospheric CO_2 Removal Deposits in the European Union

The lower panel in Fig. 4 illustrates an example in which the European Union would take some minor responsibility for their historical emissions by already introducing ACORDs in 2025, five years before the global budget can be assumed to be exhausted. Note that the positive

Table 2
Generation of biodegradable waste in the EU (2014), expressed in kt [36].

Household and similar	Food waste	Vegetal wastes	Paper and cardboard	Wood wastes	Common sludges	Total biodegradable
157,420	25,420	52,660	45,930	48,470	18,280	348,180

Table 3
Risk and risk management strategies associated with ACORDs.

Risks	Risk management
Political moves to divert deposits to cover public expenditure, for example, the introduction of a tax on the deposits	It is important that the deposits are protected, for example, in an independent trust fund. The risk is also mitigated by the expected strong opposition from owners of the deposit deeds to appropriation of their property.
Improper investments leading to loss in value of the deposits	Owners of deposit deeds should be represented on the board that controls the investment of deposit funds, to ensure that the funds are soundly invested to give proper revenues.
Certificates are issued for inadequate negative emissions	Robust certification standards should be developed and frequently evaluated, pending experience from the monitoring of carbon storage. Issuing of certificates should be transparent and safeguarded by public scrutiny.
Deposit deed owners postpone buying negative emissions	The value of the fees will go through a maximum (Fig. 3), which means that it is financially improper to wait too long. But it is important that the deposit fee should be sufficiently high to motivate early investments in negative emissions.
Competition for biogenic CO_2 molecules appropriated by the green transportation fuels industry could undermine the availability of biogenic CO_2 for negative emissions	Though partly mitigated by the electrification of the transport sector, this risk is real. A possible solution could be to regulate the market for CO_2 molecules for use in producing transportation fuels, for example, to direct this market to molecules from DAC.
Hard-to-abate CO_2 emissions sectors are competing for CO_2 removal credits, reducing the availability of biogenic CO_2 for negative emissions	It will be necessary to accommodate legitimate residual emissions in society, for example, from agriculture. Fees on food products with significant climate impact used to finance negative CO_2 emissions to compensate for CH_4 and N_2O emissions have been proposed by Moberg et al. [37]. Agreement on what constitutes valid residual emissions is needed, to prevent sectors with reasonable abatement potential from claiming a share of the residual emissions for themselves.
Developing countries are unprepared to introduce ACORDs, undermining the 1.5 °C target	In view of the climate crisis being mainly caused by the long-standing and large historical emissions of the industrialized countries, developing countries can strongly argue that the rich countries must take the lead on CO_2 removals. This can be addressed by overcompensations; see Section 10.

emissions to be compensated for are net emissions, i.e., any compensations allowed for hard-to-abate emissions are subtracted. In contrast to the ACORDs, these compensations are not made after the actual emissions.

The middle panel in Fig. 4 illustrates how the removal of each year's emissions could be distributed over time. To simplify, it is assumed that one year's emissions will be removed from the atmosphere at a constant rate, after a short ramp-up period. Thus, emissions from 2025 will be taken back in the 2031–2082 period. The ramp-up of the negative emissions is linear from 2031, reaching a maximum at 2050, and the start of each year's negative emissions is delayed in time, as illustrated by upper panel in Fig. 4, which shows the year of emissions versus the period of removal of that year's emissions.

Here it is assumed that the yearly negative emissions are restricted to 450 $MtCO_2$/y. The potential for negative emissions in Europe is uncertain. However, it can be noted that the total biodegradable waste is 350 Mt./y (Table 2) or 300 Mt./y excluding the UK. Assuming a carbon fraction in the range 25–40 %, this corresponds to 275–440 $MtCO_2$/y. Furthermore, solid biofuel primary energy consumption was reported to be 94.4 Mtoe in 2020 [35], which corresponds to more than 400 $MtCO_2$/y. Although all this CO_2 cannot be captured, bio-CCS is not the only negative emission technology. There are several other important options, so 450 $MtCO_2$/y is likely conservative. However, the assumed restriction means that emissions made from year 2037 and onwards will face a long delay until their removal is started, as indicated by the line “start of negative emission” in the upper panel. This start, however, will be greatly facilitated by existing plants.

6. ACORDs combined with other incentives and management of risks

If ACORDs were applied in, or in parallel with, a cap-and-trade system, it would mean that the cost of the ACORDs would constitute the minimum cost of CO_2 emissions. The price of the traded emissions allowances in the cap-and-trade system can be expected to be the price level without a deposit system in place minus the cost of the deposits, i.e., as long as the difference is positive. In other words, if the ETS price is 150 €/tCO_2 when ACORDs are introduced at a cost of, for example, 120 €/tCO_2, the ETS price would be expected to fall to 30 €/tCO_2. However, if the ETS price had been lower, for example, 50 €/tCO_2, the allowances would become essentially worthless and the raised cost of emitting CO_2 would provide a stronger incentive to reduce fossil CO_2 emissions.

At present, negative emissions are not allowed in the EU ETS but there is discussion of how they could be introduced. If certified negative emissions were unconditionally admitted in a cap-and-trade system, this would normally lead to a corresponding increase in fossil CO_2 emissions. The market value of the negative emissions is created by someone that needs to buy them to be able to emit the corresponding amount of fossil CO_2. Consequently, such negative emissions would not contribute to lowered atmospheric CO_2. Thus, the important difference is that while the ACORDs will neutralize the emissions allowed in the EU ETS, the direct introduction of negative emissions in the EU ETS would only neutralize increased fossil CO_2 emissions above what is allowed.

It would, however, be possible to reduce the total allocation of emission rights to neutralize this effect. Thus, any negative emissions traded would reduce the coming allocations and auctions of allowances correspondingly. However, this does not solve the key problem for incentivizing the majority of the needed negative emissions, namely, the large part of the negative emissions that need to be made after the fossil CO_2 emissions are made, as illustrated by Fig. 1. Therefore, the direct introduction of negative emissions in a cap-and-trade system will not be effective as a means of obliging emitters to finance any major share of the large negative emissions needed in the future.

The general idea behind ACORDs could of course also be implemented in part using different mechanisms, for example:

- a CO_2 tax earmarked for buying negative emissions,
- a fee on aviation used for buying negative emissions, and
- using incomes from selling or auctioning emission rights in a cap-and-trade system to buy negative emissions.

The funds created for buying negative emissions by such schemes could also sell credits to companies doing voluntary compensations.

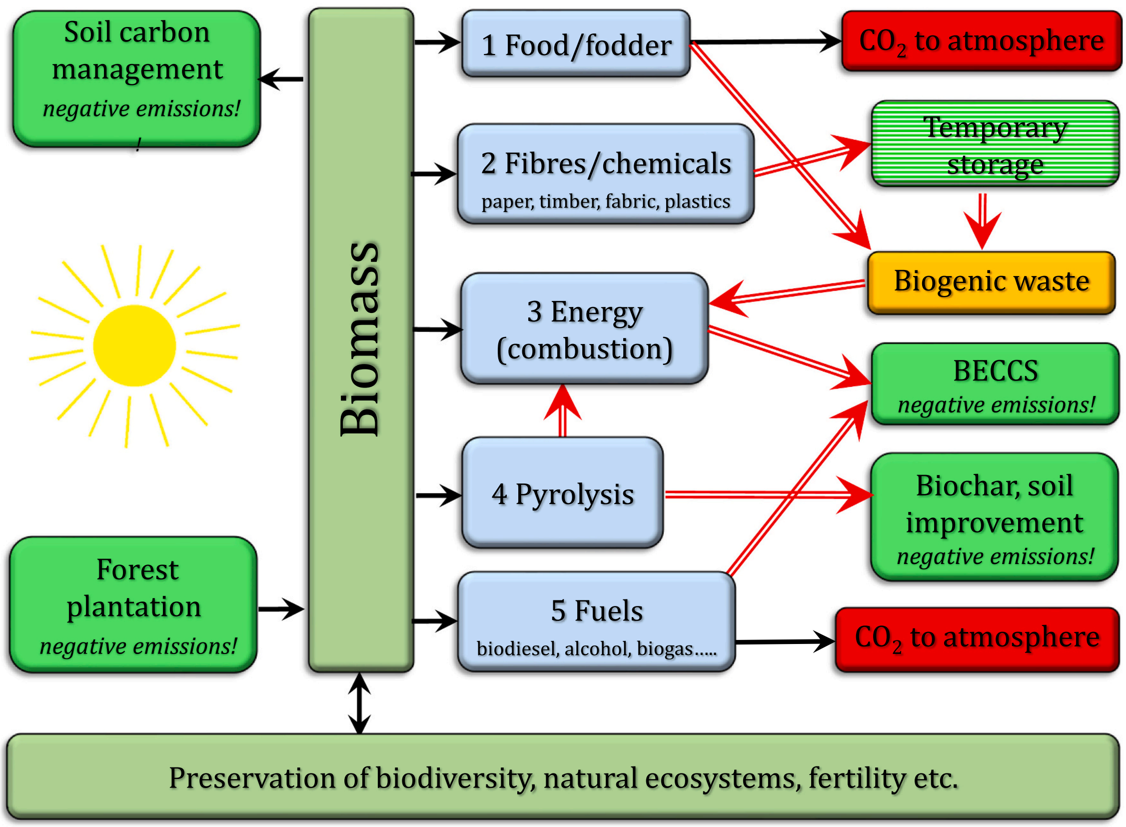

Fig. 5. Overview of pathways to mitigate climate change with biomass, i.e., reducing fossil CO_2 emissions, biospheric storage, and bio-CCS.

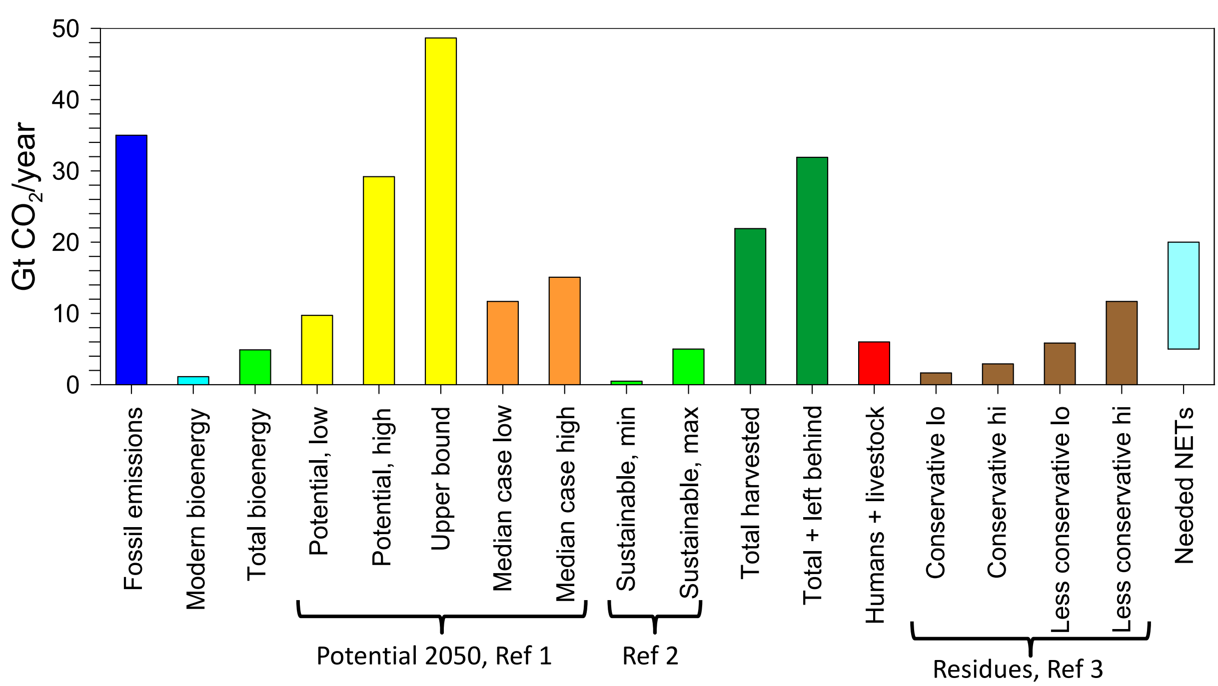

Fig. 6. Examples of estimations of available biomass for energy: Ref 1 [48], Ref 2 [51], and Ref 3 [47].

However, such schemes have the disadvantage that negative emissions are bought by public funds and not the market. As previously mentioned, it could be a challenge to protect such public funds from being used for other purposes [24]. The money locked into ACORDs, on the other hand, is the property of the deposit deed owners, although the money can only be unlocked through certified negative emissions. Potential risks associated with ACORDs, and risk management strategies, are further discussed in Table 3.

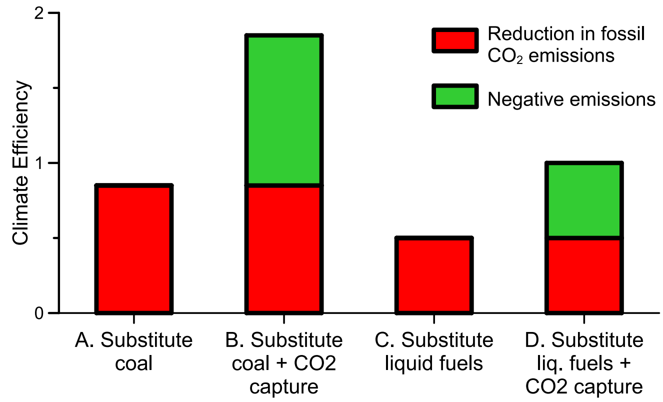

Fig. 7. Climate efficiency.

7. Negative emission technologies

7.1. Biomass-based negative emissions

Fig. 5 shows an overview of the possibilities to address climate change using biomass. In addition to direct combustion of biomass, waste from food/fodder production can be used, as well as waste or waste streams from various other biogenic products, including biochar and transportation fuels. Some products, such as building timber, may also provide temporary storage.

7.1.1. The green sink: Forestation and raised soil carbon content

Afforestation and reforestation are very attractive options for taking CO_2 from the atmosphere, as they normally come with other valuable benefits, including possible future biomass harvest. Normally, afforestation/reforestation comes at a moderate cost, although the task of estimating the actual negative emissions is not without challenges. Furthermore, forestation must be properly managed, for example, to avoid disrupting livelihoods [38].

Altered farming practices could raise the carbon content of soils [39]. This could both produce better soil and remove carbon from the atmosphere. As with forestry, an obvious challenge relates to the accounting and durability of such carbon storage.

7.1.2. Bioenergy with carbon capture and storage (bio-CCS)

Biogenic CO_2 can be captured from the combustion of biomass or biogenic waste, but also in connection with the conversion of biomass into biofuels or biochar, and then transported and stored geologically. Bio-CCS would normally be expected to have costs similar to those of CCS with fossil fuels, when the technology is used for capturing CO_2 in the flue gas from combustion, which is typically 15–20 % CO_2. Large-scale experience from two coal-fired power plants, Boundary Dam and Petra Nova, show a calculated levelized capture cost of 100–120 US$/t CO_2 and 60–70 US$/t CO_2, respectively [40,41]. The main cost is normally that of capture, which involves both a gas separation unit and the energy needed to drive the separation. CO_2 capture in amine solutions is the established technology, but regenerating the amines requires adding heat corresponding to 30–45 % of the heat released by the fuel when burnt [42]. However, chemical-looping combustion, which avoids the need for gas separation due to inherent CO_2 separation, has potential for dramatically reducing the energy penalty and cost, which is estimated at 20–30 €/tCO_2 [43]. The Swedish Energy Agency expects the costs of bio-CCS in the order of 100–180 €/t CO_2, including transport and storage [12]. Important deviations from a standard CCS case would be if the product is heat or combined heat and power instead of power only, or if the source of CO_2 is more concentrated, as could be the case in fuel conversion processes. The total costs are obviously dependent on many

Table 4
A qualitative summary of negative emissions.

Type	Potential	Cost	Storage safety	Development
Bio-CCS	Large	Moderate	High	Full-scale
Biochar	Limited	Moderate	Moderate	Small-scale
Forestation	Limited	Low	Low	Full-scale
Agricultural methods	Limited	Low ?	Low	Low ?
DACCS	Large	High	High	Small-scale
Enhanced weathering	Large	Moderate	High	Lab scale
Ocean liming	Large	Moderate	High	Lab scale

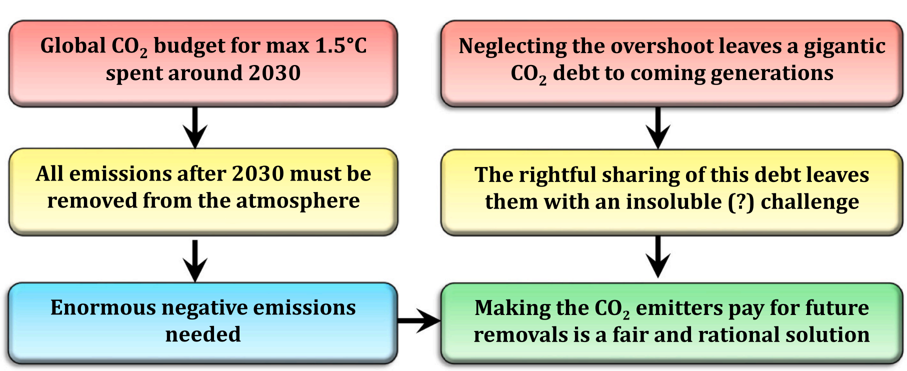

Fig. 8. The rationale of the proposal.

Table 5
Fuel heating values.

	Woody biomass [61]	200 biomasses [62], average	200 biomasses [62], median	Biomass, Slade et al. [47]	Biomass, Chum et al. [48]	Average, 16 coals [61]
Calorific heating value, MJ/kg	15.8	19.1	19.2	18	18	28.7
Carbon content, %	42.5	48.4	48.9	48.4/48.9[a]	50	70.4
Higher heating value per CO_2, MJ/kg CO_2	10.1	10.6	10.9	10.1/9.98	9.82	11.1
Lower heating value (dry), MJ/kg	17.3					30.9
carbon content (dry), %	50.0					70.4
Lower heating value per CO_2 versus moisture content, MJ/kg CO_2:						
dry	9.45					10.8
10 % moisture	9.3					10.7
20 % moisture	9.1					
30 % moisture	8.9					
40 % moisture	8.5					
50 % moisture	8.1					

[a] Assumed.

factors, such as plant size and type, transportation, and storage costs. Aker Energy offers CCS at a fixed price of 70–150 €/tCO_2, depending on local conditions. This price includes investment, operation, transportation, and storage [44].

7.1.3. Biochar

Biomass can also be converted to biochar, which can be used for improving soil quality. Since properly produced biochar is resistant to degradation, it also stores carbon in soils. Biochar is produced through the pyrolysis of biomass, producing a pyrolysis gas that can be burned or converted to liquid fuels. One advantage of biochar is the possibility of deploying small-scale pyrolysis units, for example, compared with bio-CCS. The scale-up of biochar deployment, on the other hand, offers challenges. While biochar can offer substantial co-benefits compared with bio-CCS, obvious disadvantages are that the energy in the char is lost and that only part of the carbon in the biomass will end up in the char. Thus, a mass and energy balance found that more than half of the fuel energy was lost with the char, whereas only 53 % of the carbon in the feedstock was trapped in the biochar [45]. Furthermore, 38 % of the input energy could be recovered. If such a unit were equipped with CCS, it would also be possible to prevent the carbon not trapped in the biochar from returning to the atmosphere. This would typically double the positive effect of biochar with respect to the climate.

7.1.4. Availability of biomass

The total amount of biomass available for negative emissions in the future is uncertain. It has been suggested that the scale of biomass needed would require vast plantations of energy crops. However, the possibility of using the large waste streams of biomass already harvested should be considered first.

The gross primary production of biomass captures 440 GtCO_2/y [46]. The 220 GtCO_2/y that is captured above soil is called the net primary production. Total human appropriation of biomass is around 320 EJ (32 GtCO_2), of which 100 EJ (10 GtCO_2) is discarded as residues or otherwise destroyed during harvest [47] (see Appendix 1 for EJ to Gt conversion). Thus, the extracted amount of 219 EJ/y (22 GtCO_2/y) [48] is 10 % of the net primary production. Respiration from human beings and livestock releases 2.5 and 3 GtCO_2/y, respectively [49]. The remainder of the carbon, 16 GtCO_2/y, is found in either waste streams or products such as timber, paper, clothes, chemicals, and pulp liquor. If possible to collect, the waste streams can be used in combustion to produce energy and/or biogenic CO_2. The products constitute temporary storage of carbon and can be recycled, with the latter lowering the need for raw materials and energy and increasing the temporary storage time. However, eventually these materials will become waste that can be used to produce both energy and biogenic CO_2 that can be safely stored. Biomass used for energy is 57 EJ, or 5.7 GtCO_2/y [50]. An overview of the data is shown in Fig. 6, together with some assessments focusing on biomass for energy. Note the large range of data for biomass available from Chum et al. [48] and Creutzig et al. [51] and for residues from Slade et al. [47].

7.1.5. Climate efficiency

Despite the large potential for using biomass to achieve negative emissions, the yearly yield of biomass is limited and the efficiencies of and priorities for its use to combat climate change need to be considered. Here climate efficiency is defined as the amount of CO_2 that has been removed from, or, alternatively, not emitted to the atmosphere, divided by the amount of CO_2 taken up by the biomass used to achieve this:

$$\textit{Climate efficiency} = \frac{CO_2 \textit{ removed from, or not emitted to, atmosphere}}{CO_2 \textit{ captured by biomass harvested}} \quad (1)$$

If we use biomass to substitute coal, case A, this efficiency has a maximum of around 0.85 (see Appendix 1). The efficiency can be doubled if the biogenic CO_2 is also captured and stored, case B (see Fig. 7). If the biomass is instead converted to transportation fuels, typically half of the energy content is lost, case C, which could mean halving the climate efficiency compared with case A. The loss of energy content, however, involves a similar loss of carbon content, and this carbon can be captured, leading to case D.

It can be argued that making liquid fuels, case C, is better than substituting coal if there are good CO_2-neutral alternatives to coal. On the other hand, it can be argued that there are normally also alternatives to liquid fuels and that the climate efficiency is higher for negative emissions in case B, even if reduced fossil CO_2 emissions are not considered. If liquid biofuels are to be produced, at least the waste stream of CO_2 should be used, as in case D. The conflict between the two uses of biomass, i.e., for negative emissions or for liquid fuels, must be taken seriously. We may not have so many options for negative emissions at reasonable cost besides bio-CCS, so if an important part of the biomass will be used for making liquid fuels, this would put the large future negative emissions at risk.

7.2. Direct air carbon capture and storage (DACCS)

DACCS removes CO_2 directly from ambient air and stores it geologically. The great advantage of not being dependent on biomass comes with a fundamental drawback: the concentration of CO_2 in flue gas is up to 500 times higher than in air, which means that the capture process needs to increase the concentration of the CO_2 by a factor of 2500 instead of five or six. It goes without saying that DACCS must be more expensive than bio-CCS.

An important part of the capture cost is the contactor, i.e., the device that establishes contact between the air and the compound that captures the CO_2. Capturing 5 $MtCO_2$/y from a coal-fired power plant with a monoethanolamine-based scrubber would require two absorption towers with a width and height of 17 and 23 m, respectively [52]. Assuming a cross-sectional flow of 1.4 m/s in a DACCS unit absorbing 75 % of the CO_2, a structure with a cross-section of 200,000 m^2 would be required to capture 5 $MtCO_2$/y. This corresponds to a structure 20 m high and 10 km long.

The energy needed to capture 1 tCO_2 with DACCS is of the same order as the energy produced when burning an amount of coal releasing 1 tCO_2 [42]. So in any energy system relying on coal power, it would make more sense to reduce coal power than to build DACCS. Life-cycle analyses show that for countries with a carbon footprint of electricity production of 0.37 $kgCO_{2e}$/kWh [53], which is the US average, the net removal achieved through DACCS is 20 % of the CO_2 stored, whereas in the case of Germany, with 0.56 $kgCO_{2e}$/kWh, the net removal is even negative, i.e., −25 % of the CO_2 stored. That said, DACCS can be expected to be part of the solution and novel approaches may reduce costs and energy demands.

7.3. Enhanced weathering

Enhanced weathering involves the mining and crushing of minerals that react with CO_2 to form carbonates, minerals that could be distributed over, for example, farmlands. Each tCO_2 removed typically requires the mining, crushing, and distribution of 1–2 t of minerals. The cost could be 60 US$/$tCO_2$ using dunite, and the potential as large as 95 Gt/a [54].

7.4. Ocean liming

Ocean liming involves the calcination of limestone, $CaCO_3$, the capture and storage of the CO_2 released from calcination, and distribution of the lime, CaO, in the surface water of oceans. For each CO_2 molecule released from the limestone, the lime will capture 1.6–1.8 CO_2 molecules from the air [55]. An obvious disadvantage is the energy need and cost of calcining limestone. If the process is performed similar to conventional lime production, albeit with CO_2 capture, the CO_2 from the fuel used for the calcination must also be captured. A more costly option would be to use renewable electricity for calcination. A preliminary assessment suggests a cost of 70–160 US$/$tCO_2$ [55]. A challenge is the proper distribution of the lime, whereas an advantage of ocean liming could be a local rise in pH if the lime is distributed in areas where ecosystems are harmed by increasing acidity.

7.5. Summary

A qualitative summary of different options for negative emissions is given in Table 4. Together, they provide considerable potential for the removal of greenhouse gases.

8. The cost of climate mitigation using ACORDs

The costs of the mitigation measures that would meet the global climate targets cannot be predicted with certainty, but it is possible to estimate finance needs and to assess what would be reasonable and manageable costs based on the carbon intensity in the economy. The carbon intensity is the CO_2 emissions divided by the gross domestic product (GDP). The global GDP based on purchasing power parity (PPP) in 2019 is estimated to be $134.8 \cdot 10^{12}$ to $135.3 \cdot 10^{12}$ US$ [56,57], whereas global CO_2 emissions were approximately 36.7 Gt [58], resulting in a carbon intensity of 0.27 $kgCO_2$/US$. The carbon intensity has decreased, and was likely around 0.25 $kgCO_2$/US$ in 2022. In 2027, the global GDP (PPP) is projected to be $211 \cdot 10^{12}$ US$ [56]. With current emissions levels, the carbon intensity will be 0.17 $kgCO_2$/US$. Using the carbon intensity, the scale of a mitigation cost or mitigation incentive can be estimated as a fraction of global GDP.

$$\textit{Cost as fraction of global GDP} = CO_2 \textit{ intensity} \times \textit{mitigation cost (average)} \tag{2}$$

Using a carbon intensity of 0.2 $kgCO_2$/US$ and assuming introduction of a CO_2 price of 1 US$/$kgCO_2$, this price would correspond to 20 % of the global economy, which is likely unrealistic. However, an incentive in the range of 0.1–0.2 US$/$kgCO_2$ would correspond to 2–4 % of global GDP and would be more realistic. This would roughly correspond to one year of growth in the economy and be sufficient to incentivize CCS and several negative emission options (see Section 7).

An incentive, however, is not an actual cost to society but is a transfer of money. The actual societal cost comes from the responses to such an incentive, i.e., when actions are taken and practices or behaviour are changed to avoid paying for such a cost incentive. The cost of this response is reasonably easy to assess when it comes to market adaptations, such as switching to renewables and energy savings, but less easy to assess when it comes to changes in behaviour, such as travelling by train instead of car. When it comes to market adaptations, an incentive of 0.1 US$/$kgCO_2$ would trigger actions that reduce emissions throughout the cost range of 0–0.1 US$/$kgCO_2$. A cost on CO_2 emissions would unleash market forces, triggering both known and unknown ways to reduce CO_2 emissions efficiently. Potential co-benefits could also arise, such as the reduction of pollutants associated with health effects and acid rain.

The cost of ACORDs, as well as other parallel mitigation actions, can be expected to lead to substantial reductions in emissions, i.e., a fall in the CO_2 intensity. This gives room for raised ACORD fees, which in turn could promote further emissions reductions. Increased ACORD fees would allow both more expensive negative emissions and/or raised ambitions through over-compensation (see Section 10).

9. The required retention time of carbon stored by negative emissions

An important question when discussing negative emissions is the needed storage time. Ideally, storage would be permanent. However, some of the proposed options for negative emissions could be associated with reversal, for example, through forest fires and insect damage, risks that could be further triggered by climate change. Furthermore, it may be difficult to safely assess the long-term leakage rates. Reaching the large negative emissions needed will likely require a mix of technologies having different expected retention times and different degrees of safety with respect to leakage.

The impact of leakage has been investigated in a model in which 800 $GtCO_2$ was captured by negative emissions and stored [59], corresponding to a reduction in the atmosphere of 52 ppm. If all CO_2 stored leaked out rapidly, i.e., 1 %/year, the leakage would nevertheless be somewhat lower than the natural removals. Thus, the atmospheric content of CO_2 would fall despite the leakage, i.e., assuming no fossil CO_2 is added. The natural removals include dissolution of seafloor carbonates, weathering of terrestrial carbonate rocks, and silicate weathering. Thus, it can be concluded that negative emissions with high leakage could also be very helpful.

In the case of geological storage, well-regulated storage in regions with moderate well densities was estimated to have a 50 % probability of leakage remaining below 0.0008 %/y, with over 98 % of the injected CO_2 retained in the subsurface over 10,000 years [60]. For such slow leakage, the difference between leakage and no leakage cannot be seen even after 10,000 years. After 100,000 years, the added contribution to the atmosphere is 1 ppm [59].

10. Equity, overcompensation, and directed compensations

When addressing the necessity of negative emissions for meeting climate targets, the issue of the unequal share of the climate debt cannot be ignored. Following the established principle of common but differentiated responsibilities, the rich countries must lead the way and shoulder a larger burden of negative emissions. This can be addressed by introducing a gradually increasing overcompensation in the ACORDs in well-developed countries. As the CO_2 intensity falls, the societal costs of increasing overcompensation can be accommodated.

By overcompensation is meant that the emitter is forced to buy deposits that are in excess of the actual emissions, for example, an emitter of 1.0 tCO_2 needs to pay a deposit for the removal of 1.5 tCO_2 from the atmosphere. In addition to equity-related arguments, there could be several reasons for the need to introduce such overcompensation:

- Failure to introduce ACORDs or any similar system in time on a global scale means that the carbon budget is exceeded without any existing liabilities to remove the overshooting CO_2. Thus, there will be historical emissions that need to be removed from the atmosphere to meet the carbon budget.
- In the interest of lowering the fossil CO_2 emissions, a high price of CO_2 is obviously helpful, and overcompensation would lead to higher prices, thus further lowering fossil CO_2 emissions as well as increasing negative emissions.
- Some negative emissions, such as forest plantations and agricultural methods to increase the content of carbon in the soil, are associated with significant uncertainties with respect to the safety of storage (see Section 9). Therefore, it could be relevant to introduce overcompensation for such carbon removal options.

Another tool to control negative emissions would be to introduce limits on specific negative emission technologies, i.e., a maximum of 50 % would be nature-based solutions or a minimum would be non-biogenic. Motivations for such interventions could be:

- Such interventions would ensure that the mix of negative emissions includes a minimum amount of safely stored carbon.
- In the case of a minimum fraction non-biogenic negative emissions, such as DACCS, ocean liming, and enhanced weathering, this could be included to relieve the pressure on biogenic negative emissions by creating a parallel market for more expensive negative emission technologies not dependent on biomass.
- Such interventions could also be used in combination with overcompensation, for instance, to achieve more negative emissions, without increasing pressure on biogenic negative emissions while increasing the costs of fossil CO_2 emissions.

11. Conclusions

Various aspects of negative emissions have been discussed here, the technologies and their potential, cost, and state of development, as well as the need for negative emissions and the impact of leakage. Bio-CCS is expected to have an important role, although its potential is difficult to assess. The future need for negative emissions, perhaps 10–20 $GtCO_2$/year, can be compared to the human extraction of biomass, at 22/32 (net/gross) $GtCO_2$/year, which is 10–15 % of aboveground net primary production. Bio-CCS could rely on waste streams from this extraction in many cases, instead of competing with other uses of biomass. The role of other removal technologies will depend on the availability of bio-CCS.

The main focus of the paper, however, is the challenge in finding reliable funding for negative emissions. These negative emissions will be needed to meet the Paris Agreement's temperature targets and will require significant financing, even though the specific costs, i.e., per tonne of CO_2, are comparable to those of many conventional abatement options.

Scenarios for meeting stringent climate targets involve CO_2 budget overshoots resulting in the need for large negative emissions in the later part of this century. Such overshoots would burden coming generations with a substantial carbon dept., in the order of 100 US$/$tCO_2$ or more for the removal of overshooting emissions. Thus a carbon debt of 100 tCO_2 per human being – a scenario that, unfortunately, is not unlikely – would generate a global financial burden in the order of 10,000 US $/capita or more.

In view of the high future costs of generating sufficient carbon removals, the difficulties in agreeing on how these costs should be shared among and within nations, and the budget competition with other urgent public spending needs, it is not realistic that the negative emissions needed will be paid for via public funding. Not solving the financing of negative emissions in time could mean that we are handing over an insoluble problem to our children and grandchildren.

The carbon budget for a maximum warming of 1.5 °C will likely be exhausted around 2029–2030. All emissions of CO_2 made after that point must be removed from the atmosphere to fulfill the target of a maximum warming of 1.5 °C. The most simple, fair, rational, and sustainable solution to fund this is to make the CO_2 emitters pay for these needed removals.

A system to make emitters liable for their emissions must consider that the removals needed will normally take place long after the fossil CO_2 emissions were made (see Fig. 1). To ensure that financing is available when needed, emitters should be obliged to buy deposit deeds to finance the future negative emissions. Such a system, called Atmospheric CO_2 Removal Deposits (ACORDs), has been proposed and discussed in this article and the costs of such a system can be estimated as a few per cent of the global economy.

The rationale of the proposal is summarized in Fig. 8. An ACORD system can also be extended to deal with inequity, as the climate injustice associated with large historical emissions can be addressed by introducing a gradually increasing over-compensation in the rich countries.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data used are available in cited publications, or can be calculated according to equations given.

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Appendix 1. Conversion of EJ to Gt CO_2 and comparison of coal and biomass

Rose and Cooper [61], reported a higher, i.e. calorific, heating value of typical commercial wood fuel of 15.8 MJ/kg with 42.5 % carbon, which gives 10.1 MJ/kg CO_2 (Table 5). Toscano et al. [62], investigated elemental composition and higher heating value of 200 biomasses, including the following classes: Forestal 84, Arboreous 7, Agro-industrial 34, Herbaceous 17, Nuts 16, Faecal matter 7, Seeds and oilcake 35. Average and median heating values were 19.1 and 19.2 MJ/kg, whereas the carbon content was 48.4 and 49.2 % respectively, which corresponds to 10.9 and 10.6 MJ/kg CO_2. Slade et al. [47], based his data on a higher heating value of 18 MJ/kg, which, with the above carbon contents gives 10.1 and 9.98 MJ/kg CO_2. Chum et al. [48] assumed 50 % carbon content and 18 GJ/t, which corresponds to 9.82 MJ/kg. In this work a conversion factor of 10 EJ/Gt CO_2 = 10 MJ/kg CO_2 is used.

With respect to substituting coal for biomass, it can be noted that both the calorific value, and the lower heating value, per carbon is higher for coal than for biomass. Thus, for the substitution of coal for biomass, the climate efficiency will always be somewhat lower than unity. For the higher heating value, the ratio is 0.91, whereas it is 0.8–0.85 based on the lower heating value assuming moisture content of 20–40 % for biomass and 10 % for coal.

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