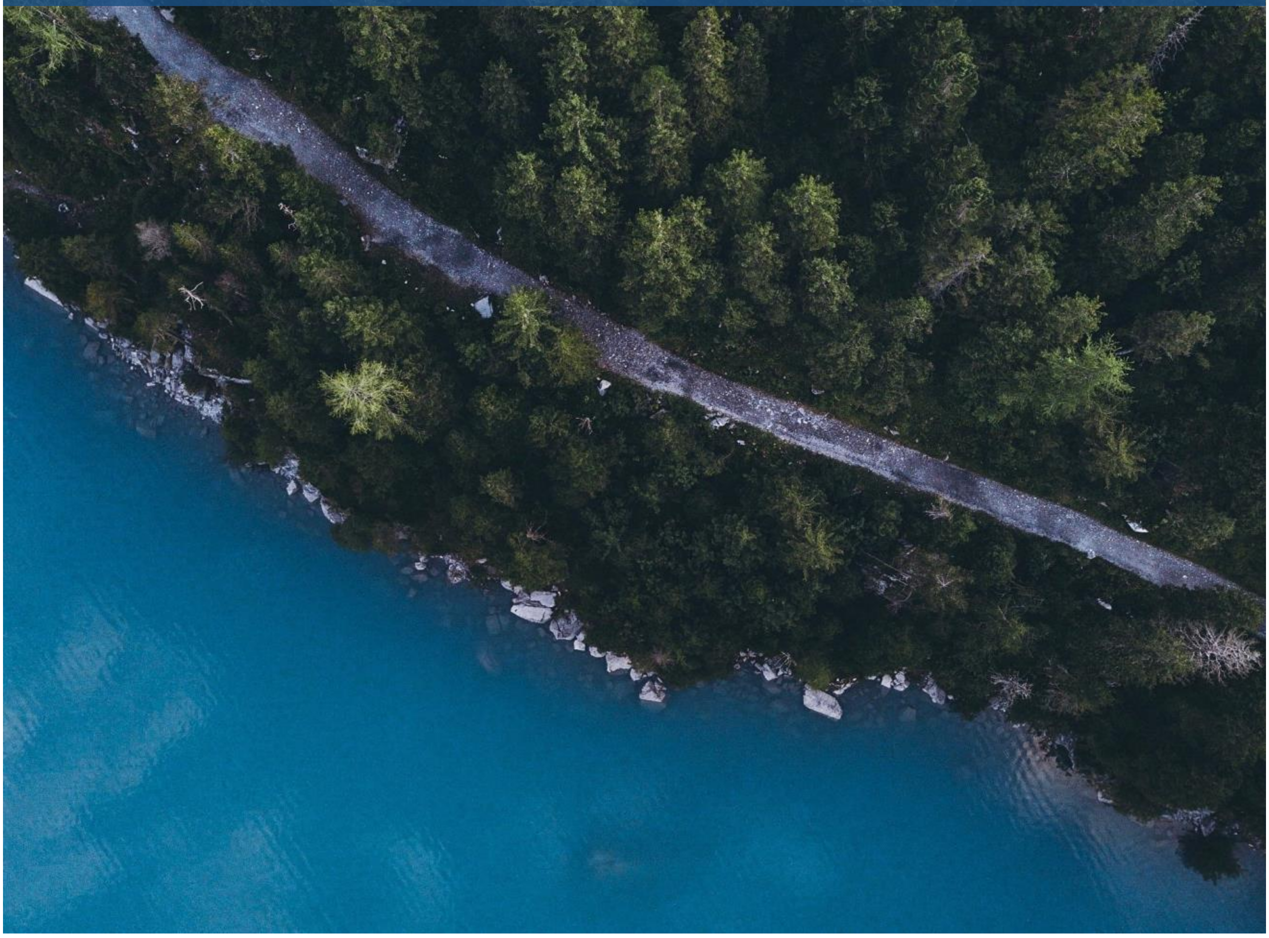
International Carbon
Action Partnership

Emissions Trading Systems and Net Zero: Trading Removals



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Executive Summary

The need for removals

To stand a good chance of limiting warming to 1.5°C, global carbon dioxide (CO_2) emissions must reach net zero by 2050 – and be net-negative thereafter. Heeding to this challenge, a number of jurisdictions have put forward net zero emissions targets. Achieving net zero implies making deep cuts in emissions across all sectors and regions and that any residual emissions be compensated by carbon dioxide removals (CDR – hereafter referred to simply as "removals") by negative emission technologies (NETs). Emission overshoots in decarbonization trajectories will also require compensation by removals. Overall, *achieving a mid-century 1.5°C target implies cumulative removals in the realm of 100 to 1000 GtCO$_2$e before 2100* - the equivalent of approximately 20 years of current annual GHG emissions.

While removals are undoubtedly part of the "net" zero equation, there is not yet consensus on the appropriate balance between removals and emission abatement, the type of technologies[1] that should be used to remove CO_2, or which policy tools are best suited to foster research, development and deployment of NETs at the required scale.

A primer on negative emission technologies

NETs cover a broad range of options to capture *and* store carbon. Both the capture and storage stages of the process are essential. Specifically, the NET must result in an *overall reduction in atmospheric CO$_2$*.[2] Moreover, the NET must provide an extremely high degree of certainty that the captured CO_2 will not be released back into the atmosphere; that is, the reduction in atmospheric CO_2 must be permanent (for NETs vulnerable to reversals, robust mechanisms are necessary to address this risk). Several options are currently being explored (for additional details and a summary see Section 3.2):

- *Afforestation and reforestation* (AR) is currently the most mature and readily available removal option. It does, however, present important challenges with regards to permanence, competition for land, and, potentially, biodiversity.
- *Soil carbon sequestration* (SCS) is the result of practices that enhance the soil carbon content, such as refraining from deep ploughing, or sowing cover crops. These practices can increase soil quality and are ready for deployment, but quantification of removals and saturation remain challenges.
- *Biochar* (BC) involves the production of charcoal from biomass (through pyrolysis or gasification), which can then be added to soil. This can store the carbon in a stable way and improve soil quality.

[1] Throughout this report, the term "negative emissions technologies" is used to refer to the various ways that carbon could be removed from the atmosphere and stored. This includes options such as afforestation and reforestation.
[2] Note that not all activities that involve carbon capture and storage lead to overall reductions in atmospheric CO_2. Capturing and storing carbon from a natural gas power plant, for example, would *reduce emissions that go into the atmosphere* (that is, it would at best be near carbon neutral), but would not *remove emissions from the atmosphere* (that is, it would not generate a removal). Only in rare cases can carbon capture and use be said to generate a removal.

- *Bioenergy with carbon capture and storage* (BECCS) combines energy production (electricity, heat, or hydrogen) from biomass with carbon capture and storage (CCS) of the CO_2 emitted, resulting in a net removal. It can conflict with food production/security and with biodiversity.
- *Direct air carbon capture and storage* (DACCS) involves filtering CO_2 out of the ambient air through chemical processes and storing it. A key advantage is that this technological approach can be massively scaled up, but it requires a lot of zero-carbon energy and is currently a high-cost NET option.
- *Enhanced weathering* (EW) accelerates natural CO_2-binding processes from the decomposition of minerals such as basalt. In this technological approach to removals special rocks are mined, ground and spread over agricultural or brownfield land and coastal land or ocean surfaces. EW could improve soil quality and help counteract ocean acidification but requires an extensive infrastructure and zero-carbon energy and could cause air and water pollution.

Balance, caution and the need for societal debates

The NETs presented above differ significantly in terms of their costs, potential scale and permanence. They can also trigger positive and negative side effects, which can help or hinder progress towards sustainable development goals.

On the one hand, removals can play an important role in alleviating the financial burden of the transition towards decarbonized economies, thereby allowing for a larger portion of residual emissions and buying time to develop and deploy lower cost abatement technologies. The importance of this effect should not be underestimated: a recent review of 1.5°C degree scenarios finds that the median global carbon price (measured in 2005 US$) for achieving this target is $145/tCO_2$ in 2030, around $380/t CO_2 in 2050 and at least an order of magnitude above this by 2100. Prices will differ across the scenarios assessed based on different assumptions regarding technology deployment and costs. However, across all scenarios, carbon prices increase towards the end of the century as lower cost abatement opportunities become exhausted. Currently, existing carbon prices are significantly lower than those envisioned in the 1.5°C degree-consistent scenarios and cover about 22% of global emissions. Importantly, experience to date shows that even modest carbon prices can generate concerns surrounding carbon leakage for emission-intensive and trade-exposed firms, as well as adverse impacts on low-income households – which, in turn, threaten the political sustainability of carbon prices at the levels required to achieve deep decarbonization.

On the other hand, relying heavily on removals carries important challenges and risks. From an investment perspective, allowing removals to compensate for a lack of abatement brings additional uncertainty surrounding future carbon prices and returns on abatement investments. Added uncertainty surrounding both removal technology developments and policy choices might discourage abatement today, thereby delaying learning and locking economies into higher emission pathways and continued dependence on fossil fuels.

Adverse environmental impacts should also be considered. NETs that require large scale plantation of biomass (e.g. afforestation or BECCS), for example, may create potential land-use conflicts as well as negative impacts on food security, energy security, and biodiversity conservation. Measures such as enhanced weathering may also lead to ground, water and air pollution.

Choices surrounding abatement and removals will also endure ethical debates, with social responsibility at the center. Environmental justice groups, for example, have long seen offset crediting mechanisms as a deferral of emission reduction responsibility from industrialized nations to least developed countries, and the acceptance of large-scale removal policies will likely face similar conflicts if they are perceived to relieve polluters of their responsibility to curb their emissions. Intergenerational equity is also important, as today's failure to reduce emissions increases removal burden (and likely corresponding costs) as well as climate change impacts for future generations. There may also be reluctance to accept high levels of societal dependence over removal measures, and important challenges in the governance of large-scale removal measures may also arise.

Societies are thus unlikely to be agnostic about the final balance of abatement and removals in the net zero equation. Ultimately, the balance of abatement and removals in deep decarbonization pathways must be the result of societal debates that take the local tradeoffs between costs and opportunities of large-scale CO_2 removals into account. Nevertheless, research indicates that removals are now a necessary part of the climate solution, particularly in the second half of the century.

Policy support for research, development and deployment of NETs

The large variation in technological status and estimated scale across NETs calls for a diverse set of instruments - operating on both supply- and demand-side factors - to ensure that the right incentives are in place for their research, development and deployment at scale.

First, support for research and development (R&D) is crucial and can take many shapes, such as publicly funded environmental innovation programs for universities and research councils, as well as fiscal incentives for R&D activities through the provision of tax breaks, among others. Basic R&D is a low-regret option because the scale of removals required during this century necessitates the joint deployment of several NETs, many of which are in the research and demonstration stage and may not be deployed until much later in the century.

Second, support for deployment can be facilitated through the generation of *removal units* (RUs). Once the technological readiness level of a NET approaches commercialization, policies could focus on ensuring there is sufficient demand for RUs in the market, providing a revenue stream for the operators of NETs and allowing them to scale up their operations.

At one extreme, a government may directly purchase RUs through public procurement paid for using general revenues to, for example, comply with its domestic and international targets. This could be done through reverse auctions or pre-announced prices (similar to feed-in-tariffs for renewable energy projects). The key advantage of this approach would be that the government can determine the scale of the removals procured through this market and provide a dependable source of demand for removals. At the other extreme, the government could let voluntary actions by citizens and businesses be the main demand driver for RUs. This, however, is unlikely to lead to a level of demand that can deliver the scale of removals required for limiting temperature change to 1.5°C.

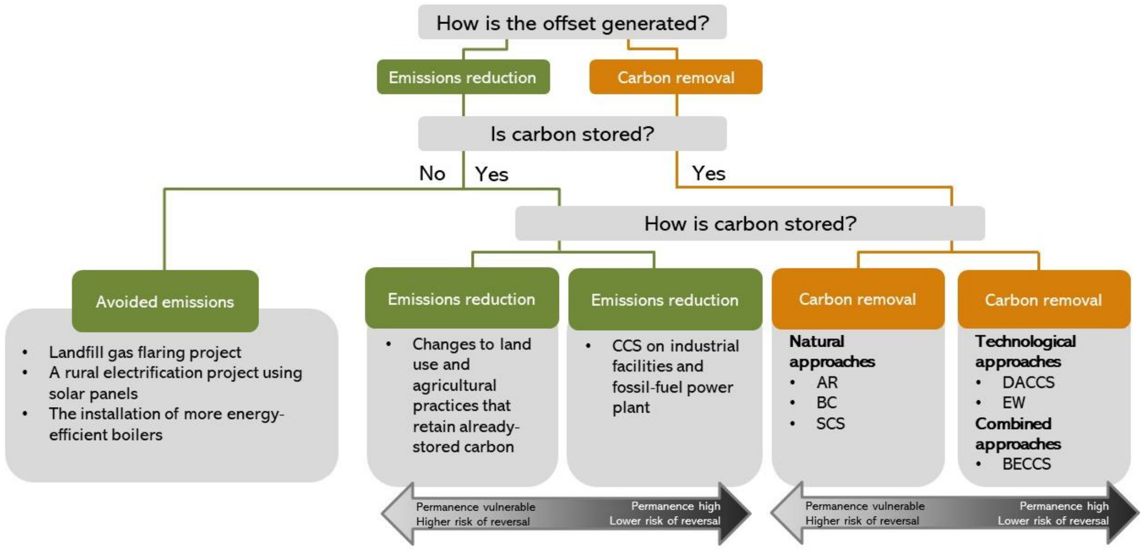
In between these two extremes are several hybrid options, such as mandating removal obligations on private entities, providing fiscal incentives through tax credits, or directing public procurement policies towards climate-neutral suppliers. Moreover, a connection between the market for RUs and any existing carbon pricing instrument – such as an emissions trading systems (ETS) – could be created.

Establishing removal unit certification mechanisms

RUs are the foundation for a market where CO_2 removals are treated as a product that generates a revenue stream for their producers. The existence of a robust certification mechanism for generating high-quality RUs, including measures for ensuring the permanence of removals, is thus important for all NETs (the permanence component being particularly important for NETs that rely on biological sinks).

In this respect, it is critical to differentiate between *RUs* and current *offset credits*. As outlined above, NETs entail the capture *and* storage of carbon. Specifically, the activity must result in an *overall reduction in atmospheric concentrations* – such that greenhouse gases that had previously been in the atmosphere are removed and permanently stored elsewhere. This approach contrasts to most of the offset credits available to date, which are generated using a baseline-and-credit approach: a landfill gas flaring project, for example, can *reduce* the volume of emissions that is released into the atmosphere, but it will not *remove* emissions that had previously been in the atmosphere. RUs can thus be treated as a subset of offset credits, and not all offset credits are RUs (See Figure 4).

Figure 4: Taxonomy of carbon offsets



Note: CCS is carbon capture and storage; AR is afforestation and reforestation; BC is biochar; SCS is soil carbon sequestration; DACCS is direct air carbon capture and storage; EW is enhanced weathering and BECCS is bioenergy with carbon capture and storage.

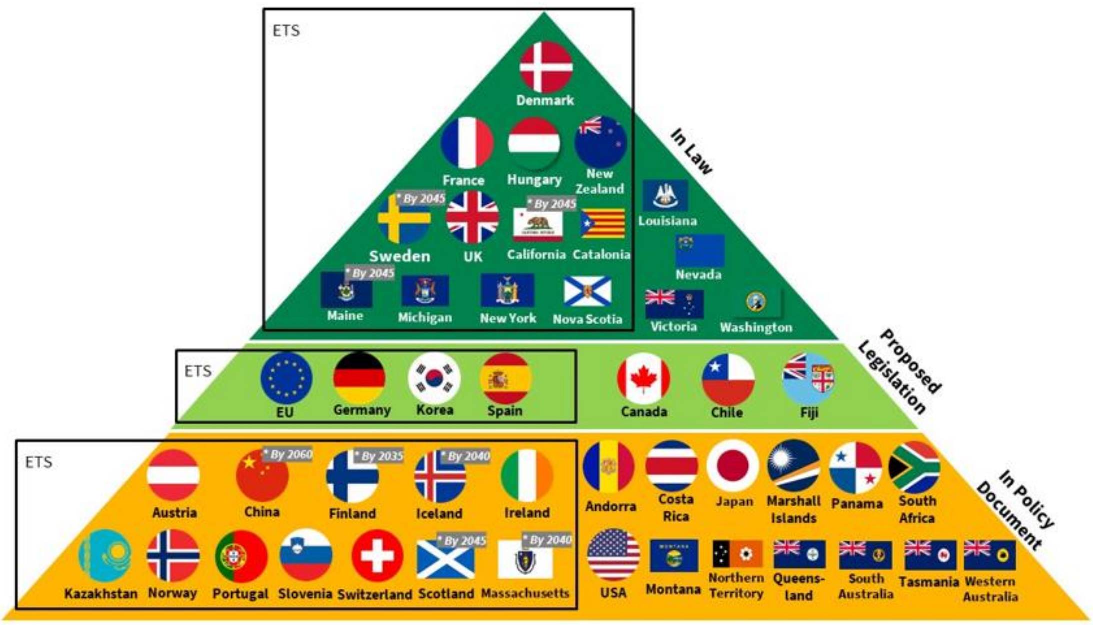
Source: based on University of Oxford (2020) and UNEP (2017)

In designing certification mechanisms for RUs, regulators would have to define the *technological scope* (what types of NETs should be eligible to generate RUs?); the *geographical scope* (where should the credited activities be located?); and the *governance arrangements* (who should govern the certification mechanism?). This entails making several important decisions, such as whether to prioritize certain technologies over others (e.g. favoring those which render themselves to robust quantification and permanence), whether to procure RUs domestically and/or internationally, and to what extent governments are willing to cede control over the certification mechanism to third parties. To ensure environmental integrity of units, regulators will also need to establish rules and processes which must be put in place to make sure that RUs are additional, permanent and conservatively quantified, and that transfers of RUs are tracked so as to avoid double-counting, while taking into account the important particularities of NETs in this regard.

ETSs and net zero

Although there is a range of ETS-operating jurisdictions with active or proposed net zero targets in place (see Figure 2), the concrete role that ETSs will play in reaching net zero, as well as the impact of net zero targets on ETS design, is not yet clear. An important consideration is that, even under ETSs with stringent caps and other aggressive climate policies, certain GHG emissions – such as those from aviation, hard-to-decarbonize industrial processes and agriculture – are likely to be too costly or impossible to eliminate in the near term.

Figure 2: Net zero targets and their status of development



Source: Adapted from the Net Zero Tracker of eciu.net (as of 30 Mar. 2021). Information on the status of net-zero target development (i.e. "in law", "in proposed legislation" and "in policy document") is drawn from the Energy & Climate Intelligence Unit's Net Zero Tracker, accessible at https://eciu.net/netzerotracker, except for Germany, which was updated at the request of the jurisdiction. The categorization is accurate as of 31 March 2021.The list of jurisdictions may not be exhaustive and excludes municipalities, cities and the private sector.

Net zero targets reframe the long-term prospects for an ETS with different conceivable options. For example, caps could be maintained at a non-zero level to accommodate for some amount of residual emissions, fall to zero or even become negative if the responsibility of covered entities shifts from abating emissions to removing them from the atmosphere. In either case, the role that ETSs play is bound to evolve. Yet, there is little research on the practical considerations of a net zero cap, let alone what it would mean to have a "negative" one. A zero cap could be the natural continuation of current systems – but without any allocation of new allowances, and possibly making use of RUs. What a negative cap would entail, however, is less clear. A negative cap would mean not only that regulated entities would have to reduce their emissions to zero, but also that a removal purchasing obligation (that is, a liability) would have to be allocated to such entities through the ETS – even after their (net) emissions reach zero. How this could be done – and how to address the likely concerns over cost, loss of international competitiveness and carbon leakage – requires further research.

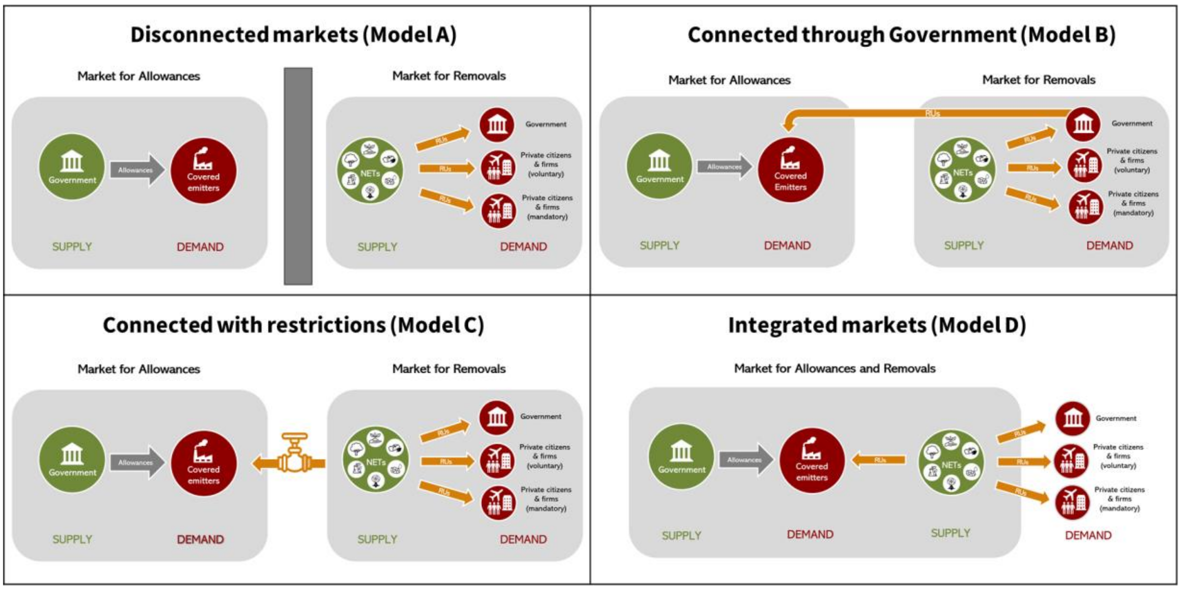
Some ETSs already have experience with the use of RUs, albeit primarily in the context of offsets from afforestation and reforestation projects. Examples include California, some Chinese Pilot ETSs (such as those in Beijing, Fujian and Hubei) as well as the Korean ETS – all of which established quantitative limits and qualitative criteria for offset use. New Zealand's ETS awards allowances for removals from forestry (afforestation and reforestation), without a limit on the total number of units from those activities that can go into the system.

While ETS caps may stay positive or merely reach zero under a policy package for a jurisdictional net zero target, the necessity to reach net-negative emissions in the second half of the century begs the question of who will pay for the necessary removals, and how. This entails not only a discussion on if (and how) to integrate removals into the ETS, but also on much broader and important topics of burden sharing across jurisdictions, across sectors (within a jurisdiction), and over time. These discussions go well beyond ETS policy design and may need to be embedded within international agreements. They will have consequences on how many removals a jurisdiction will be required to generate and are, therefore, important considerations for the role of the ETS. The allocation of removal obligations is an important area of further research and is likely to be a focus of essential debates on economic effectiveness, fairness, equity and competitiveness.

Options for interactions between ETSs and removals

The market for removals can interact in different ways with an ETS, depending on the direct or indirect connections the government may create between the two. The nature of these interactions will, to a large extent, be driven by differentials between the price for allowances and the price of RUs. We describe four generic models of the possible relationships between the ETS and the removals market (see Section 4 for a full description).

Figure ES 1: Models A-D



Source: authors' own elaboration.

Model A: Disconnected markets

- *Concept*: In Model A, the ETS and the removals market are completely disconnected. This means that the ETS does not make use of any RUs, although RUs could be used outside of the ETS.
- *Main opportunities*: Model A has the key advantage that incentives for emission reductions under the ETS are separated from the incentives for removals, thereby providing more long-term certainty for investors in abatement technologies under the ETS, who will not be exposed to the risk that their investments in GHG abatement are rendered unprofitable by the availability of cheaper removal options in the future. This also alleviates concerns about high-carbon lock-in due to myopic behavior and uncertainty about the future supply of RUs.
- *Main constraints*: Under Model A, regulators cannot use the ETS as a source of demand to incentivize NETs more directly. There is also no avenue to compensate for residual emissions within the ETS – meaning that the ETS cap would likely have to stay positive, with residual emissions within the ETS being compensated by RUs outside the ETS. Market dynamics under the ETS could also worsen over time: as emissions approach zero, the number of market players would shrink, and low market liquidity and unbalanced market power could hinder effective price discovery and market function Finally, insofar as the government aims to make use of RUs outside of the ETS, and if the responsibility for the purchase of these units falls on the government itself, this could entail an increase in expenditure by the government.

Model B: Connected through government

- *Concept*: In Model B, the ETS and the removal market are connected through the government, who buys RUs and sells or distributes them in the ETS (and, therefore, controls the supply of RUs into the ETS). RUs can then be used within the ETS in a myriad of ways (such as in reserves, as free allocation and as extra allowances at auctions).
- *Main opportunities*: Under Model B, the government controls the influx of RUs and, as a result, retains control over the balance of abatement and removals under the ETS. At the same time, under this Model the ETS can incentivize NETs through demand for RUs. An important advantage of Model B is the possibility for the government to bridge the large gap between the high cost of many NETs and (current and near-term forecasts of) allowance prices – thus providing demand for RUs even in the case of large price differentials. This could enable differentiated treatment across technologies, thereby offering support that accounts for differences in technological readiness. Moreover, the use of RUs provides a compensation avenue for residual emissions within the ETS, such that the ETS cap can be positive, zero or negative.
- *Main constraints*: The introduction of RUs into the ETS can create uncertainties for market players about the costs of producing RUs and their (future) availability, and potentially impacting the market price and expectations thereof. This model provides only limited respite to the issues of market liquidity and market power under the ETS when emissions approach zero due to the limited number of market players. The fiscal balance for the regulator would thus depend on the price paid for RUs in the removals market, on whether RUs are sold by the regulator under the ETS and for what price, and on price impacts (such as decreased auction revenues) due to the higher availability of units under the ETS. By having the government buy and sell RUs, Model B places a high administrative burden on the regulator.

Model C: Connected with restrictions

- *Concept*: Under Model C, the allowance and removal markets are connected directly, through transactions between ETS-covered entities and removers. The government, however, can still place qualitative and quantitative limits on the transactions between the two markets.
- *Main opportunities*: Model C retains most of the opportunities of Model B, with the notable exception that the effectiveness of the ETS as a source of demand for RUs would depend crucially on the price differentials between the ETS and the removals market. Compared to Model B, Model C has the advantage of lower fiscal and administrative burdens on the regulator.
- *Main constraints*: Similarly to Model B, under Model C the introduction of RUs into the ETS could impact the price (and expectations thereof) under the ETS. Yet, under Model C regulated entities would only have the incentive to purchase removals if the cost of doing so was lower than the cost of allowances. This exposes NETs to price risks, which could undermine part of the incentives for NET deployment. This model thus provides limited opportunity to support NETs through the ETS if RU generation costs exceed abatement costs under the ETS. The regulator could complement the incentives generated by the ETS by offering carbon contracts for difference (CCfDs) to address the

risks from carbon price variability and differentials, although this option would increase the fiscal costs for the regulator.

Model D: Integrated markets

- *Concept*: Under Model D, emitters and removers are part of the same market, which means that the government would issue allowances or credits to removers (e.g. as currently done in New Zealand). Under Model D there is no limitation on the number of RUs that can be used in the ETS.
- *Main opportunities*: Similarly to Models B and C, Model D offers an avenue for incentivizing NETs through the ETS, as well as compensation for residual emissions in the ETS and flexibility in cap-setting, with limited fiscal and administrative burden. An advantage unique to Model D is that the integration of removers into the ETS may make the ETS more liquid and reduce concerns of uneven market power, as would arise when emissions under the ETS approach zero in Model A.
- *Main constraints*: Due to the absence of restrictions on the use of RUs in the ETS, under Model D the government would not be able to guide choices on abatement vs removals. Regulated entities could risk facing an effective allowance price ceiling imposed by removal costs of eligible NETs, which could delay investments in mitigation and lead to a high-emissions lock-in – possibly making long-term targets more expensive to reach. Moreover, and similarly to Model C, the direct connection between the ETS and the removals market would mean that the ETS could provide limited incentive to NETs in the case of large price differentials. Here again, CCfDs could provide an avenue for additional support by the government, complementing the incentive from ETS demand but increasing fiscal costs.

Conclusions and questions for further research

Current decarbonization trajectories rely heavily on removals in the second half of the century – the need to remove 100 to 1000 $GtCO_2e$ before 2100 represents a massive societal, environmental and technological challenge, which should ideally happen in parallel with – and not detract from – efforts to rapidly and drastically abate emissions.

ETSs could play a role in addressing this challenge. The various models on interactions between ETSs and removals explored in this paper differ primarily in terms of the level of government control over the balance of abatement and removals in the system; the flexibility on cap-setting and how to deal with residual emissions; the impacts on the market expectations that could lead to myopic behavior and high carbon lock-in; the avenues for additional support for NETs in the case of large price differentials between allowance and removal prices; and the resulting fiscal and administrative burden on governments aiming to achieve net zero.

The present analysis has identified several areas of further research. Some of these relate to the responsibility for, and the methods for deploying, removal activities: who should be responsible for acquiring RUs? If the government, then how could this be financed and operationalized? If the private sector and/or individuals, how and on what basis should the obligation be distributed? These questions become particularly critical in the context of large emission overshoots, which would require large volumes of removals in the second half of the century, for which no clear financing path is yet available.

This study does *not* aim to advocate for the use of RUs in ETSs. Rather, its objective is to contribute to the still incipient discussion on RUs by summarizing the state of knowledge, outlining theoretical options and comparing them. It is also important to note that several policy options – unrelated to ETSs – could be employed to incentivize the research, development and deployment of NETs. Further investigation would be necessary to understand the merits and challenges of these different policy options to incentivize NETs. Further research could also delve deeper into the models described here – for example, under Model C, more clarity is needed on what restrictions could foster the twin goals of deep decarbonization and large-scale removals. Other options not investigated here – such as discounting in the use of RUs and employing different unit types for different technologies or risk profiles – would also benefit from further investigation.

Whether or not removals are used in and incentivized through ETSs, it is crucial to adequately quantify and certify any RUs that are generated. A robust certification mechanism for generating high-quality RUs, including measures to ensure their permanence, is important for all NETs. Further research is necessary to establish best practices and ensure environmental integrity in the generation of RUs – this involves complex questions such as when a removal can be said to have taken place (e.g. in the context of carbon capture and use); ensuring that life-cycle emissions and removals are taken into account, also in the context of a counterfactual baseline (e.g. when determining criteria for sustainable biomass); as well as ensuring permanence (e.g. through technological choice) and/or establishing reliable mechanisms to address any reversal risks.

Furthermore, while this analysis focuses on the questions of "if" and "how" ETSs could interact with RUs, the question of "when" this could or should take place also merits further research: the wide-ranging potential impacts of interactions between ETSs and removal markets call for caution and careful analysis before effecting policy changes. Several questions also remain unanswered with regards to the alignment of ETS caps with net zero (or net negative) targets. Within an ETS, what does it mean, in practice, to have a zero cap, or even a negative cap? What arrangements are necessary to transition away from positive caps? How would market dynamics in the ETS look as emissions approach zero?

Whether or not RUs are integrated into ETSs, the financing of such removals remains highly uncertain, and decisions in this respect entail important considerations of burden sharing across jurisdictions, across sectors, and over time.

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Acronyms

AR	Afforestation and reforestation
BC	Biochar
BECCS	Bioenergy with carbon capture and storage
CCfD	Carbon contract for difference
CCS	Carbon capture and storage
CCU	Carbon capture and utilization
CCUS	Carbon dioxide capture, utilization and storage
CDR	Carbon dioxide removal
CO_2	Carbon dioxide
DACCS	Direct air carbon capture and storage
ETS	Emissions trading system
EU	European Union
EU ETS	European Union Emissions Trading System
EW	Enhanced weathering
GDP	Gross Domestic Product
GHG	Greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
LULUCF	Land-use, Land-use change and forestry emissions
MRV	Monitoring, reporting and verification
NET	Negative emission technology
NZ ETS	New Zealand Emissions Trading Scheme
R&D	Research and development
RD&D	Research, design and development
RU	Removal unit
SCS	Soil carbon sequestration

1 Introduction

To avoid the most severe social, economic, and environmental impacts of climate change, the parties to the Paris Agreement aim to reach net zero GHG emissions in the second half of the century.[3] The parties invited the Intergovernmental Panel on Climate Change (IPCC) to assess the impacts and pathways of limiting warming to 1.5°C, which revealed that doing so would require that global carbon dioxide (CO_2) emissions reach net zero by 2050 and be net-negative thereafter. This implies making deep cuts in GHGs across all sectors and regions and compensating for any residual emissions with an equal mass of carbon dioxide removal (CDR – hereafter referred to simply as "removals") from negative emission technologies (NETs) (Luderer et al., 2018). Emission overshoots in decarbonization trajectories will also require compensation by removals (Geden & Schenuit, 2020; IPCC, 2018; Chapter 2).

Heeding these challenges, more and more jurisdictions worldwide are adopting net zero emissions targets. According to Black et al. (2021), by March 2021, 124 countries implemented or were considering implementing net zero emission targets. These countries represent 61% of global emissions, 52% of the global population and 68% of global GDP. Outside of national commitments, a supranational jurisdiction, as in the case of the European Union, 73 subnational jurisdictions, and 155 cities are also committing to net zero targets at an increasing rate. Large companies have also put forward net zero targets, with at least 417 companies doing so as of early 2021.

While there is consensus on the imperative to establish net zero targets by midcentury, the policy frameworks, business models and technologies required to *achieve* these targets remain unclear. One emerging and unresolved question is on the appropriate balance between societal emissions on the one hand and removals from NETs on the other. Given that the costs of abatement will increase as we seek to squeeze out the remaining emissions from our economies, some have pointed to removals as a means to alleviate the financial burden of the transition, thereby allowing for a larger portion of residual emissions and buying time to develop and deploy lower cost abatement technologies (Burke, Byrnes, & Fankhauser, 2019). However, others have cautioned against such a strategy based on environmental integrity and ethical grounds – e.g. potential land-use conflicts for measures that require large scale plantation of biomass; concerns about scalability, long-term permanence, safety and costs of some measures; concerns about the equivalence between emission reductions and removals, especially in the context of emission overshoots; as well as the concern that removal policies could alleviate polluters of their responsibility to curb their own emissions, leading to mitigation obstruction and high carbon lock-in, among other problems (Honegger, Michaelowa, & Roy, 2020; Lenzi, 2018; McLaren, Tyfield, Willis, Szerszynski, & Markusson, 2019; Whitmarsh, Xenias, & Jones, 2019; Zickfeld, MacDougall, & Matthews, 2016).

Emissions trading systems (ETSs) and carbon taxes are prominent and effective climate change mitigation policy instruments that play an important role in reducing emissions, provided certain conditions are met (Best, Burke, & Jotzo, 2020). For example, ETSs can function particularly well when covered entities have technologies at their disposal to reduce their emissions, when sectors with a high consumption of fossil fuels are covered, or when covered sectors have relatively low abatement costs (Ball, 2018). Especially when looking

[3] Article 4.1 of the Paris Agreement

at the emission reductions in the electricity sector, ETSs have played an important role in these achievements by acting as a main driver to make coal-based electricity generation less attractive.

On a more general level, ETSs have evolved over 15+ years, with 22 systems currently in operation and many more under development or consideration around the world (ICAP, 2021). However, despite ETSs' prominent role in reducing emissions, their ability to contribute to the achievement of net zero targets is yet to be tested beyond picking the low hanging (abatement) fruits.

In this paper, we seek to understand the challenges that net zero targets could present for the operation of ETSs and to develop a series of options (or 'models') for the possible interactions between ETSs and removal units (RUs) from NETs. We first assess the current state of net zero targets as well as the emerging academic and policy debate in this area. We then review removal technologies and a broad set of policies to support their development and deployment, and then conceptualize different models for the integration of removals into an ETS. These models are compared against possible policy objectives.

Table 1 outlines the main terms and definitions relevant for this discussion.

Table 1: Definitions of important terms (based on (IPCC 2018; Annex I)

Term	Definition
Anthropogenic removals	Anthropogenic removals refer to the withdrawal of greenhouse gases (GHGs) from the atmosphere as a result of deliberate human activities. These include enhancing agricultural, forestry and land use biological sinks of carbon dioxide (CO_2) and using chemical engineering to achieve long-term atmospheric removal and permanent geological storage by combining biomass combustion or direct chemical air capture with geological storage, among others.
Net zero emissions	Net zero emissions are achieved when anthropogenic emissions of GHGs to the atmosphere are balanced by anthropogenic removals over a specified period.[4]
Net zero CO_2 emissions	Net zero CO_2 emissions are achieved when anthropogenic CO_2 emissions are balanced globally by anthropogenic CO_2 removals over a specified period. In the paper and for simplicity, 'carbon' and 'CO_2' are used interchangeably.
Net zero target	A temporal target at which net zero GHG or net zero CO_2 emissions are to be reached.
Carbon (i.e., CO_2) neutrality	Net zero CO_2 emissions are also referred to as carbon neutrality.
Climate neutrality	Concept of a state in which human activities result in no net effect on the climate system. Achieving such a state would require the balancing of residual emissions with GHG emission removal as well as accounting for regional or local biogeophysical effects of human activities.

[4] To date, the vast majority of negative emission technologies relate to the removal of carbon dioxide emissions. Technologies for the removal of non-CO_2 gases are still very incipient.

Negative emissions	Removal of greenhouse gases (GHGs) from the atmosphere by deliberate human activities, i.e., in addition to the removal that would occur via natural carbon cycle processes.
Net negative emissions	A situation of net negative emissions is achieved when, as a result of human activities, more GHGs are removed from the atmosphere than are emitted into it.
Net negative target	A temporal target at which net negative emissions are to be reached.
Carbon dioxide removal (CDR)	Anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. This includes existing and potential anthropogenic enhancement of biological or geochemical sinks and direct air capture and storage but excludes natural CO_2 uptake not directly caused by human activities.
Carbon capture and storage (CCS)	Process in which a relatively pure stream of CO_2 from industrial and energy-related sources is separated (captured), conditioned, compressed and transported to a storage location for long-term isolation from the atmosphere.
Carbon capture and utilization (CCU)	Process in which CO_2 is captured and then used to produce a new product. If the CO_2 is stored in a product for a climate-relevant time horizon, this is referred to as carbon dioxide capture, utilization and storage (CCUS). CCU may or may not lead to negative emissions, depending on how the CO_2 is used and for how long it is stored.

2 Net zero targets, role of removals and the role of ETSs

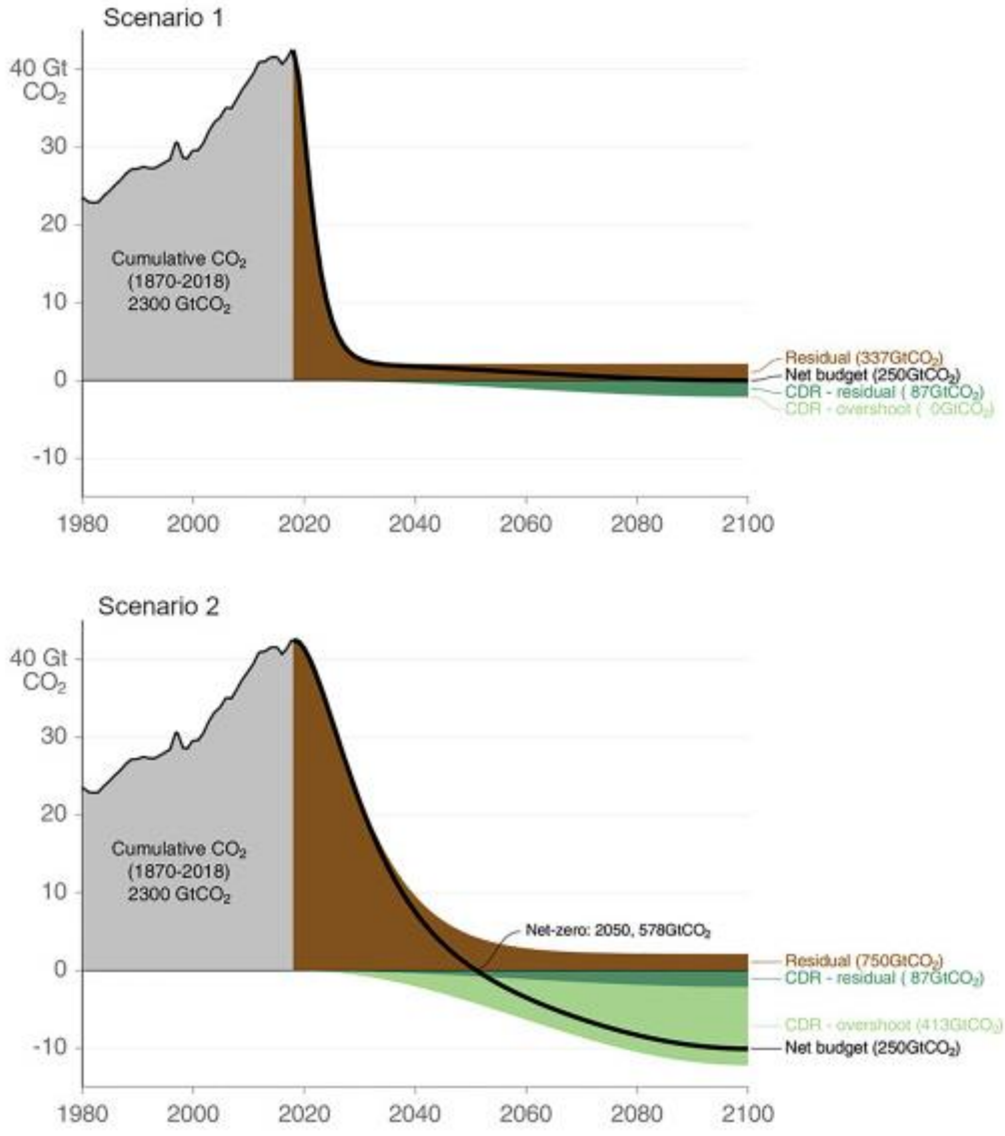
Several considerations are relevant for the translation of net zero goals into concrete policy responses. The sections below outline economic, environmental, ethical and political considerations at a broad societal level, as well as some elements specific to ETS design.

2.1. Understanding the "net": abatement versus removals

While removals are undoubtedly part of the "net" zero equation, there is not yet consensus on the appropriate balance of emission abatement and removals, nor on how many and when removals should take place, nor on the type of technologies used for removal (Friedmann, Zapantis, & Page, 2020; Fyson et al., 2020; Honegger et al., 2020; Rickels, Proelß, Geden, Burhenne, & Fridahl, 2020). As the concentration of GHGs drives climate change, the climate will largely be agnostic to the final balance. However, societies' tolerance for residual emissions as well as for emissions overshoots will determine the required amount and timing of removal activities for a given warming target. Navigating this tradeoff requires economic, environmental and ethical considerations.

Under a 1.5°C target, the available scenario evidence so far suggests a remaining carbon budget between 420–580 $GtCO_2$ and an additional +/- 250 Gt CO_2 for non-CO_2 GHGs (IPCC, 2018; Chapter 2.2.2.2) compared to annual global GHG emission levels at 52.4 $GtCO_2e$ (excl. LULUCF) in 2019 (Olivier & Peters, 2020). There are different pathways to 1.5°C that have consequences for remaining residual emissions as well as for removals to compensate for "overshooting" concentration targets. An immediate and drastic decrease in emissions could put us on a path where a reasonably small level of removals - less than 100 Gt cumulatively – would be required to compensate for residual emissions (Fuss et al., 2020). A more likely scenario, even with sharp emission reductions over the coming decades, includes the need for removals to compensate for residual emissions plus large scale removals to compensate for emission overshoots, thus reducing atmospheric GHG concentrations in line with a threshold compatible with a 1.5°C target. See Figure 1.

Figure 1: Emission and stylized pathways that emit less than 250 Gt CO2 between 2019 and 2100 to limit temperature increase to 1.5°C in 2100



Source: (Fuss et al., 2020)

The stark implication here is that achieving a mid-century 1.5°C target could imply cumulative removals in the realm of 100 to 1000 Gt CO_2e before 2100 (IPCC, 2018 Chapter 2.3.4.1)- the equivalent of approximately 20 years of current annual GHG emissions. To place this in context, in the 2005-2014 period global removal levels from forestry (afforestation and reforestation) amounted to an annual average of 3.9 Gt CO_2e (Grassi et al., 2018). Given the current technical status of many removal technologies (reviewed below), the bulk of these activities will need to take place post 2030. Importantly, debates about how to finance such large-scale volumes of removals – including who should pay for them – are sorely needed.

Estimates of abatement costs for achieving a 1.5°C target vary across modelling scenarios as well as across assumptions surrounding, e.g., economic and population growth, technological development, energy and resource efficiency, and consumer trends. For example, Dietz et al. (2018) review a range of scenarios and find that the median global carbon price (measured in 2005 US$) for achieving the 1.5°C target is $145/tCO_2$ in 2030, around $380/t CO_2 in 2050 and at least an order of magnitude above this by 2100. Prices differ across the assessed scenarios based on different assumptions regarding technology deployment and costs. However, across all scenarios, carbon prices increase towards the end of the century as lower cost abatement opportunities become exhausted.

These carbon prices are at least an order of magnitude higher than the majority of existing carbon prices, which only cover about 22% of global emissions (World Bank, 2020). Yet, experience with carbon pricing shows that even modest prices generate concerns surrounding carbon leakage for emission-intensive and trade-exposed firms, as well as regressive impacts on low-income households (Verde, Acworth, Kardish, & Borghesi, 2020). These observations call for policy frameworks that assist industry to decarbonize while remaining internationally competitive (Acworth, Kardish, &Kellner, 2020) as well as ensure that low income households have the resources required to respond to higher fossil fuel prices (Haug, Eden, & de Montes Oca, 2018).

Even under aggressive climate policies, certain GHG emissions – such as those from aviation and hard-to-decarbonize industrial and agricultural processes – will be too costly or impossible to eliminate by mid-century (Fuss et al., 2018 Chapter 2.1). As long as some emissions remain positive, removals through the application of NETs will be necessary to achieve net zero GHG emissions (Geden, Peters, & Scott, 2019; Rogelj et al., 2015). Removals may also be used as a means of constraining costs for some sectors and buying time for the deployment of advanced technologies (Burke et al., 2019). Such use of carbon removals deserves careful reflection. From an investment perspective, allowing removals to compensate for a lack of abatement brings additional uncertainty surrounding future carbon prices and returns on abatement investments. Added uncertainty surrounding both technology developments and policy choices might discourage abatement today, delaying learning and locking economies into higher emission pathways (Hepburn et al., 2019). At the same time, however, delaying implementation of removal options means delaying learning on NET deployment and, hence, the necessary upscaling of removals, which will make it more difficult to achieve the negative emissions required after mid-century.

There are also important environmental and ethical considerations when determining the appropriate balance of abatement versus removals. This is particularly the case for NETs that require large scale plantation of biomass (e.g. afforestation or bioenergy with carbon capture and storage - BECCS) that may create potential land-use conflicts and negative impacts on food security, energy security, and biodiversity conservation (see Buck (2016) for a recent summary). For example, in the case of BECCS, negative side effects may include direct and indirect land-use changes, food security issues, biodiversity losses, deforestation and forest degradation or health impacts through an increase in nitrogen oxide (NO_x), particulate matter (PM), and other health-related pollutants (Minx et al., 2018). These concerns are not new, and there is limited social acceptance of large-scale energy crop cultivation for bioenergy production (Waller et al., 2020).

Social acceptability constraints may also hamper NETs that make use of geological sequestration of CO_2. Taking CCS, which is an integral component of several mitigation and NET options, as an example: the technology has been around for almost a century, yet it has only recently progressed beyond the demonstration stage. This is true despite a growing consensus on its importance in decarbonization scenarios (Friedmann, Zapantis, and Page 2020; IEA 2019) and is, in part, due to a host of concerns which include perceived risks from transport and storage as well as concerns that a broad application in the electricity sector would delay the phaseout of fossil-based generation. There are some concerns that CCS is an excuse to strive for a long-term solution for the continued use of fossil fuels (Acatech (Ed.), 2018; Whitmarsh et al., 2019). However, in the context of mandatory coal phaseouts as well as the competitiveness of renewable energy technologies for electricity production, a renewed debate has begun on a limited role for CCS to accommodate residual emissions from hard to abate industrial processes, as well as from electricity generation from gas. A consensus on the final role of CCS in achieving net zero will have implications for the adoption of NETs and will likely differ by region. The social acceptability of technologies perceived to be more “natural” (such as those related to forestry and to soils) is significantly higher, despite the potential for lower permanence and vulnerability of such technologies to reversals (IPCC, 2019).

Social acceptance will also be linked to the design of programs that generate RUs and the measures taken to mitigate reversal risks and ensure permanence. As discussed in Section 2.2, jurisdictions like California have put measures in place (e.g., a forest buffer account) to mitigate reversal risks for the use of forest offsets in their ETSs in order to ensure permanence, which also facilitates their social acceptance. It remains to be seen to what extent permanence measures developed in the context of various crediting mechanisms worldwide render themselves to addressing permanence risks at much bigger scales of RU use.

Public engagement can play an important role in addressing social acceptance issues. In addition to societal debates on decarbonization pathways, affected parties and the general public should be involved at an early stage when implementing removal measures, and an active and disclosed strategy of minimizing potential risks should be offered (Acatech (Hrsg.), 2018; Whitmarsh et al., 2019). Public awareness campaigns that transparently communicate the costs, risks and benefits of different NETs as well as of alternatives can also contribute to mutual trust and understanding between policymakers and the public.

Choices surrounding abatement and removals will also endure ethical debates, with social responsibility at the center. Environmental justice groups have long seen offset crediting mechanisms as a deferral of emission reduction responsibility from industrialized nations to least developed countries (Blum & Lövbrand, 2019). The acceptance of large-scale removal policies will likely face similar conflicts if they are perceived to alleviate polluters of their responsibility to curb their own emissions. Intergenerational equity is also important, as today’s failure to reduce emissions increases removal burdens (and likely corresponding costs) as well as climate change impacts for future generations (Fyson et al., 2020; Lenzi, 2018). There may also be reluctance to accept high levels of societal dependence on removal measures, and important challenges in the governance of large-scale removal measures may also arise. Hence, the scale of removals in final decarbonization pathways may also be shaped by ethical and political conflicts between divergent modes of climate and energy governance (Waller et al., 2020).

The considerations above suggest societies are unlikely to be agnostic about the final balance of abatement and removals in the net zero equation. While (co-)benefits of mitigating GHG emissions are clear and well understood (New Zealand Ministry for the Environment, 2018), the local tradeoff between costs and opportunities of large-scale CO_2 removal are not yet clear. Indeed, this uncertainty would suggest that abatement must continue to be the primary focus for, at the very least, the next decade, during which huge progress is required in emission reductions, no matter the pathway considered. However, given residual emissions from activities that are highly valued but for which technologies are not yet available, combined with the need to compensate for overshooting, removals are now a necessary part of the climate solution, particularly in the latter part of this century.

2.2. Net zero-compatible ETSs

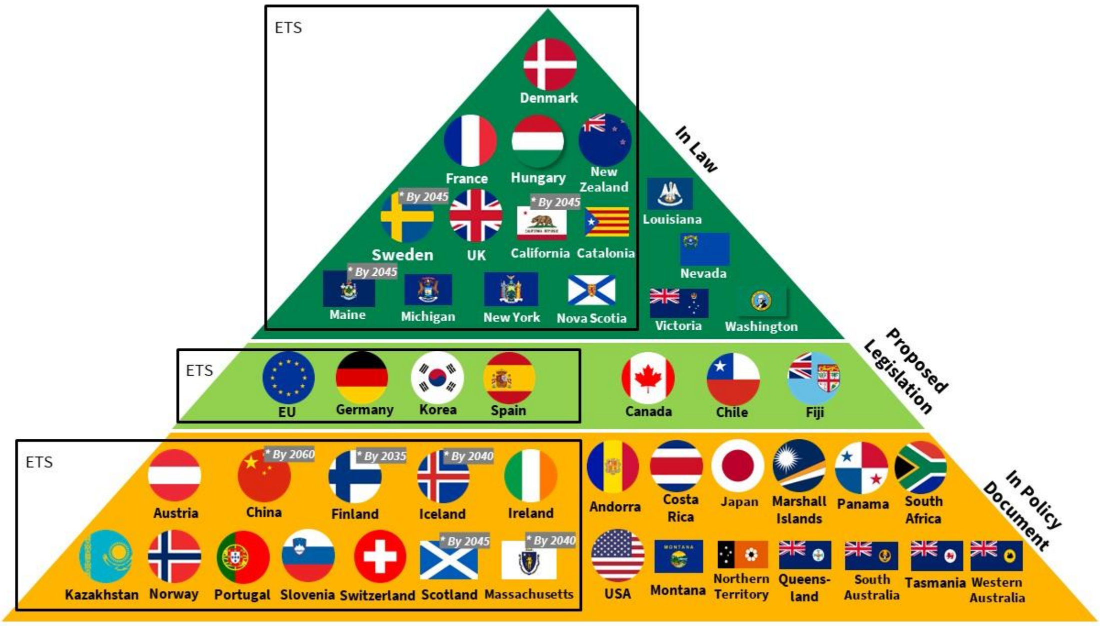
2.2.1. Design considerations

Many of the jurisdictions that have put forward net zero targets also operate an ETS – as displayed in

Figure 22 below. Most of these jurisdictions are part of the EU ETS[5], operate their own ETSs on a national (Korea, New Zealand, China) or subnational (California) level or are states that form part of the US-east coast Regional Greenhouse Gas Initiative (Massachusetts, Maine, New York).

Although there is a range of ETS-operating jurisdictions with active or proposed net zero targets, the concrete role that ETSs will play in reaching net zero, as well as the impact of net zero targets on ETS design, is not yet clear. A benefit of cap-and-trade policies is the strong signal that an absolute and declining emissions cap sends to covered entities – namely, that high-emitting facilities will not be part of the future economy (Acworth et al. 2017). For example, under the current policy setting, the EU ETS cap will reach zero in 2057. Net zero targets reframe the long-term prospects for an ETS with different conceivable options: caps could be maintained at a non-zero level to accommodate some level of residual emissions, fall to zero or even become negative if the responsibility of covered entities shifts from abating emissions to removing them from the atmosphere. Regardless, the role that ETSs play is bound to evolve as emissions under the cap approach zero.

Figure 2: Net zero targets and their status of development



Source: Adapted from the Net Zero Tracker of eciu.net (as of 30 Mar. 2021). Information on the status of net-zero target development (i.e. "in law", "in proposed legislation" and "in policy document") is drawn from the Energy & Climate Intelligence Unit's Net Zero Tracker, accessible at https://eciu.net/netzerotracker, except for Germany, which was updated at the request of the jurisdiction. The categorization is accurate as of 31 March 2021.The list of jurisdictions may not be exhaustive and excludes municipalities, cities and the private sector.

[5] Since 1 January 2021, Germany is operating an ETS for the fuels and heating sector in parallel to their participation in the EU ETS.

However, there is little research on the practical considerations of a net zero cap, let alone on what it would mean to have a “negative” one. A zero cap could be the natural continuation of current systems – but without any allocation of new allowances. In this case, policymakers could allow for the use of RUs, noting that ETSs could also function without them (see Chapter 4 for a discussion on how RUs could be integrated into an ETS). If RUs are allowed into the ETS, the ‘market’ could then pertain primarily to trades in removals, paid for by entities with residual emissions.

What a *negative* cap would entail, however, is less clear. A negative cap would mean not only that regulated entities would have to reduce their emissions to zero, but also that a *removal purchasing obligation* (that is, a liability) would have to be allocated to regulated entities through the ETS – even after such entities’ (net) emissions reach zero. The liability could be allocated on the basis of, for example, requesting more than one unit of removal for each unit of residual emissions under the ETS – although this is likely to overburden those entities and sectors with hard-to-abate emissions (and, once emissions reach near-zero, the acquisition of RUs would also diminish). Another approach to a negative ETS cap could be to allocate the liability across regulated entities on the basis of units of production or other benchmarks – this, however, could raise important concerns about cost, loss of international competitiveness, and carbon leakage. Alternatively, assuming the government has stopped issuing allowances, and that RUs are already being used in the ETS for compliance, the government could enter the ETS on the buy side and provide an additional source of demand for units currently being traded in the secondary market. This effectively implements a negative cap equal to the amount of the government purchases of units, minus additional mitigation action such purchases trigger through the implied price increase of direct government purchases.

Generally speaking, while ETS caps may stay positive or merely reach zero under a policy package for a jurisdictional net zero target, the necessity to reach net-negative emissions in the second half of the century begs the question of who will pay for the necessary removals, and how. This entails not only a discussion on if (and how) to integrate removals into the ETS, but also, much more broadly, on important topics of burden sharing across jurisdictions, across sectors (within a jurisdiction), and over time. These discussions go well beyond ETS policy design and may need to be embedded within international agreements. They will have consequences on how many removals a jurisdiction will be required to generate and are, therefore, important considerations for the role of the ETS. If liabilities are not ascribed to regulated entities under the ETS, then jurisdictions with net-negative targets would have to consider whether to purchase removals from government budgets (with the resulting fiscal burden on jurisdictional coffers – as is the case in Sweden[6]) and/or whether (and how) to assign removal purchase liabilities to private entities (that is, individuals and/or businesses) outside of the ETS. These options are not mutually exclusive, and entities regulated under the ETS could also be subject to obligations outside of the ETS.

The allocation of removal obligations is an important area of further research and is likely to be a focus of important ETS as well as social policy debates on economic effectiveness, fairness, equity and competitiveness

[6] As one of its measures to support full-scale deployment of capture, transport and storage of carbon dioxide of biogenic origin (bio-CCS) Sweden intends to apply reverse auctions for removals from bio-CCS. Under this scheme the government would purchase removals via reverse auctions, resulting in guaranteed prices for removals for the actors that win the auction (i.e. the lowest bidder). The compensation paid out to successful bidders would be the difference between the agreed guarantee price and the value of any EU funding and national funding to promote bio-CCS that an actor receives (Government Offices of Sweden, 2020).

of alternative approaches. Further research is required to better understand the legal and economic ramifications of these different approaches, as well as the impact of the functioning of the ETS.

2.2.2. ETSs and removal units: experience to date

Some ETSs already have experience with the use of RUs, albeit primarily in the context of offsets from afforestation and reforestation projects. Examples include the California cap and trade program, some Chinese Pilot ETSs (such as those in Beijing, Fujian and Hubei) as well as the Korea ETS – all of which established quantitative limits and qualitative criteria for offset use.

The California Cap-and-Trade Program, for example, allows for offsets from improved forest management, reforestation, and avoided conversion projects that are subject to both strict quantitative and qualitative limits. Also, California has adopted a Tropical Forest Standard to incentivize avoided emissions from tropical deforestation, although it is not an approved offset protocol in California's Cap-and-Trade Program. Regarding quantitative limits, starting with 2021 emissions, California has lowered the share of offsets that can be used by entities to fulfil the compliance obligation from 8% per year for 2013-2020 emissions to 4% per year for 2021-2025 emissions. This will then increase to 6% again starting with 2026 emissions when direct abatement is set to become harder and more expensive.

Regulations on qualitative limits have also been updated and aim at ensuring California's direct environmental benefits from offset use. Starting with 2021 compliance obligations, no more than one half of any entity's offset usage limit can come from offsets that do not provide direct environmental benefits in the state of California. Offsets projects located within California are considered to provide such benefits as well as some projects implemented outside of California. To ensure environmental integrity, California's offset program has incorporated the principle of buyer liability: the state may invalidate an offset credit that is later determined to have not met the requirements of an offset protocol due to double counting, over-issuance, or regulatory non-conformance (ICAP, 2021). To ensure permanence of the GHG emissions reductions generated by the offsets, provisions are in place that ensure that the carbon remains stored in trees for at least 100 years. These include monitoring, reporting and verification for 100 years after the offset has been issued as well as requirements for offset credit replacement by the forest owner in case of intentional reversals and the maintenance of a forest buffer account to provide insurance for unintentional reversals (California Air Resources Board (CARB), 2015).

New Zealand's ETS (NZ ETS) awards ETS allowances for removals from forestry (afforestation and reforestation), without a limit on the total number of units from those activities that can go into the system. Assessing the impacts of forestry coverage on removal activities under the NZ ETS shows that afforestation and reforestation levels have been directly influenced by allowance prices in the past, among other factors. Starting around 2012, when allowance prices were low, this led to decreasing afforestation levels, especially until the delinking of the NZ ETS from international markets in 2015 (Carver, Dawson, & Kerr, 2018; Manley, 2019). In addition, policy uncertainty regarding the nature of upcoming reforms as well as the stock change carbon accounting approach have proven less effective in incentivizing a higher rate of afforestation levels in the long run (Carver et al., 2018; Manley, 2020). NZ ETS reforms passed into law in 2020 aim to better incentivize afforestation while simplifying accounting measures and reducing complexity and costs for forest owners engaging with the NZ ETS.

The system's approach to the use of allowances from forestry could continue as the country moves towards net zero, and there is an expectation that forestry units will play an important role in the country's decarbonization pathway towards 2050 and beyond. This, however, is a contentious topic that is currently under debate – the nature of the approach and its significance for New Zealand's net zero pathway might change in the future.

Other jurisdictions, such as the European Union and Switzerland, are beginning to consider what role RUs could play in future ETS design. On the international level and beyond ETS, Switzerland and Peru have entered into bilateral cooperation on the implementation of mitigation activities through Article 6 of the Paris Agreement, that include the transfer of removals which are to fulfil robust requirements on the permanence and additionality of the emissions reductions achieved (Swiss Federal Office for the Environment (FOEN), 2019).

In addition to the creation of RUs, ETSs have also had to consider the role of CCS, a key component of technological and combined approaches to removals discussed in more detail in Section 3.1. In the EU ETS, for example, CCS activities are included to a limited extent – installations can reduce compliance obligations where carbon is captured and stored through a direct connection to a reservoir. While CCS of fossil fuels will increasingly need to be part of the mitigation solution in the EU, these provisions would need to be amended to allow for removals via NETs. First, the direct link between emissions and storage is likely not appropriate if storage is to be scaled up and CO_2 to be transported. Second, to accommodate BECCS, installations exclusively using biomass would need to be covered by the ETS Directive (this is currently precluded by No.1 of Annex I) (Rickels et al., 2020). However, doing so creates interactions with the Effort Sharing Directive and could result in double counting of biomass emissions. Applying a non-zero emissions factor to biomass would also have far-reaching ramifications, particularly on jurisdictions that rely on wood pellets for heating as well as the paper and pulp industry (Roth et al., 2016). Rickels et al. (2020) suggest an approach where biomass installations are awarded "additional" allowances for the carbon content that is ultimately captured.

3 Negative emission technology options and policy considerations for their support

NETs cover a broad range of options to capture *and* store carbon.[7] Both the capture and storage steps of the process are essential. Crucially, the application of an NET must result in an *overall reduction in atmospheric* CO_2 concentrations. Moreover, the NET must provide a high degree of certainty that the captured CO_2 will not be released back into the atmosphere (and any reversal risks must be mitigated). That is, the reduction in atmospheric CO_2 must be permanent.

To explore the various NET options available and how policy may facilitate their contribution to the achievement of net zero targets in further detail, Section 3.1 discusses negative emissions as a concept and highlights the role CCS and CCU can play not only for negative emissions, but also for mitigation. Section 3.2 provides an overview of the most prominent NET options. These differ not only in the way atmospheric carbon is captured and where it is ultimately stored, but also in terms of their technological development status, scalability, costs and unintended consequences. Based on these differences, Section 3.3 highlights the various considerations to take into account when designing policies to support the development and deployment of NETs.

3.1. Negative emissions and the role of CCS/CCU

The IPCC defines negative emissions as the removal of CO_2 from the atmosphere by deliberate human activities (See also Table 1 above). These activities must directly and permanently cause a reduction in the CO_2 concentration in the atmosphere. In other words, the activities themselves should emit fewer GHGs than those they remove.[8] Various technology options can produce negative emissions by relying on natural, technological, or combined natural-and-technological approaches.

Two steps are common to all NETs. In the first step, a GHG must be removed from the atmosphere such that it no longer contributes to the greenhouse effect. For example, capturing GHG emissions from a fossil fuel power plant could, at best, lead to near-zero emissions (by capturing CO_2 that would otherwise have been emitted into the atmosphere, but not removing CO_2 that had previously already been in the atmosphere). In the second step, the removed GHG must be stored in a sink where it will not be released back into the atmosphere. For example, to produce negative emissions, afforestation projects, which store CO_2 in terrestrial biomass, need to properly account for possible forest fires in newly forested areas over the lifecycle of the plantation (Jeffery, Höhne, Moisio, Day, & Lawless, 2020).

In this context it is important to underline the crucial role that CCS and CCU play for both mitigation (i.e. reduction of CO_2 emissions *into the atmosphere* by their deployment in fossil fuel power plants and industry) and for negative emissions (i.e. removal of CO_2 *from the atmosphere* by their deployment in biomass power

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[7] We focus here exclusively on removals of CO_2. While methods for removing other GHGs do exist, so far they have not been explored at length (Geden & Scheenuit, 2020).

[8] See Tanzer and Ramirez (2018) for a more detailed discussion of the considerations involved in quantifying the magnitude of negative emissions.

plants and in directly removing carbon from the ambient air) (Tamme, 2021). This dual role can have important ramifications.

First, lower-cost, widely available and modular CCS and CCU can simultaneously advance mitigation and removals. However, as discussed in Section 2.1, this may also reduce the incentives to retire fossil fuel-intensive infrastructure, particularly in developing countries (IEA, 2016). Second, the net effect of CCS and CCU on (negative) emissions must be carefully accounted for in detailed lifecycle analyses (Tanzer & Ramírez, 2019). For example, using captured CO_2 for enhanced oil recovery, in soft drink production or in building materials will have significantly different impact on emissions across different time horizons. Third, the fact that CCS and CCU can be applied in many different contexts and to achieve different goals blurs the difference between emitters and removers because both functions are sometimes performed by the same entity. Finally, provided there is interest in these technologies in a jurisdiction, the balance between CCS and CCU will depend on the ease of access to storage sites and the availability of commercial opportunities for using the captured carbon.

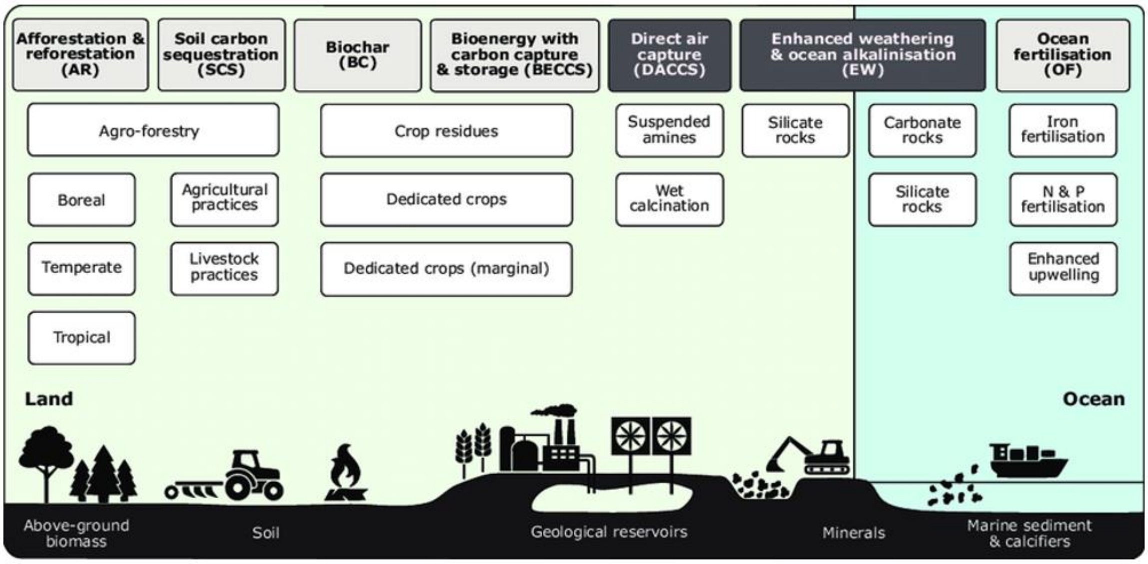
3.2. Technology options

Figure 3 illustrates the diversity of technology options for capturing carbon from the atmosphere and storing it in various sinks by enhancing biological or chemical processes. Carbon which is fixed in biomass through photosynthesis can be stored above-ground in the form of trees through afforestation and reforestation or in soils through soil carbon sequestration or biochar using *natural approaches*. Direct air capture and enhanced weathering rely on chemical processes to extract carbon from the atmosphere to then store it in geological reservoirs and rocks, respectively, and can be considered *technological approaches*. Bioenergy with carbon capture and storage uses both processes, in that photosynthesis fixes carbon in biomass which is used as feedstock to produce other forms of energy through combustion and is a *combined approach*. The carbon in the flue gases from combustion is captured through chemical processes and stored in geological reservoirs. Next, further detail is provided on the individual technologies identified in Figure 3, drawing on the reviews in Minx et al. (2018) and EASAC (2018) for the high-level assessment of technological development status, scalability, permanence of removal and costs.[9]

While policymakers have little direct control over technology development status, scalability and costs, it is essential to keep in mind that they have a crucial role to play in ensuring the permanence of removals by designing and enforcing stringent performance requirements for all NET options assessed below.

[9] Both studies underline the limited potential of and the significant uncertainties involved in Ocean Fertilization (OF) as a NET. Therefore, OF is excluded from the discussion in this paper.

Figure 3: Typology and diversity of negative emission technologies



Source: Minx et al. (2018). 'Negative emissions: Part 1 – research landscape and synthesis'. Environmental Research Letters. 13.

3.2.1. Afforestation and reforestation (AR)

AR is currently the most mature and readily available NET. It does, however, present important challenges with respect to permanence and competition for land, especially if deployed at large scales. Impacts on biodiversity can be positive or negative, depending on land use changes. As forests reach saturation, removal potential can be increased by long-term use of harvested wood (such as some building materials). Technical status: existing; Potential in 2050: up to 3.6 GtCO_2/year; Permanence: vulnerable; Costs: USD 5-50/tCO_2.[10]

3.2.2. Soil carbon sequestration (SCS)

Soil carbon sequestration results from practices that enhance the soil carbon content such as refraining from deep ploughing, or sowing cover crops – thereby also increasing soil quality. Although measures are ready for deployment (and are already being practiced), results are very challenging to quantify. Also, soils reach saturation in 20 years and are subject to reversals (e.g. if previous agricultural practices are reintroduced). Technical status: existing; Potential in 2050: up to 5 Gt CO_2/year; Permanence: vulnerable; Costs: USD 0 -100/t.

[10] Minx et al. (2018) is the most recent, comprehensive and rigorous review of the scientific literature on NETs. The current report uses it, particularly its Table 3, as the source for the estimates of global potential in 2050 and costs. Here and below, we draw on the information on technical status from Table 2 of EASAC (2018) which treats the same issues in a non-technical and more accessible way. The information on permanence relies on both EASAC (2018) and Minx et al. (2018). In particular, if a NET has "high permanency" in Minx et al. (2018) or has a "yes" in response to the question "Carbon removal secure in the long -term?" in EASAC (2018), it is indicated as having "Permanence: High" in text and in Table 2 below. Otherwise, the NET is indicated as having "Permanence: Vulnerable". It should also be noted that potential in 2050 is not additive. For example, extensive AR may compete with agricultural land and limit the potential of SCS and BC.

3.2.3. Biochar (BC)

Biochar involves the production of charcoal from biomass through pyrolysis or gasification and then adding the charcoal to soil. This stores the carbon in a stable way and improves soil quality, but the fuel source used must be assessed carefully in quantifying (negative) emissions from a lifecycle perspective.[11] Technical status: existing; Potential in 2050: up to 2 Gt CO_2/y; Permanence: vulnerable; Costs: USD 30-120/t.

3.2.4. Bioenergy with carbon dioxide capture and storage (BECCS)

Bioenergy with carbon capture and storage combines energy production (electricity, heat or hydrogen) from biomass with capture and storage of the CO_2 emitted, resulting in a net removal.[12] The removal would then be made permanent through underground storage, which may be limited in some regions. Cultivation of biomass using sustainable practices is necessary, can be land-intensive (although less so per tonne than afforestation) and conflict with food production/security and biodiversity. Alongside measures in agriculture, forestry and land-use, BECCS is the main CDR technology employed in IPCC scenarios. Technical status: demonstration; Potential in 2050: up to 5 Gt CO_2/y; Permanence: high; Costs: USD 100-200/t.

3.2.5. Direct air carbon capture and storage (DACCS)

Direct air capture with carbon storage involves filtering CO_2 out of the air through chemical processes and storing it underground, which may be limited in some areas. A key advantage is that it can be massively scaled up, but it requires a large amount of energy, which would have to be low or zero carbon. Technical status: demonstration/commercial; Potential in 2050: up to 5 Gt CO_2/y; Permanence: high; Costs: USD 100-300/t.

3.2.6. Enhanced weathering (EW)

Enhanced weathering accelerates natural CO_2-binding processes from the decomposition of minerals such as basalt. Rocks are mined, ground and spread over agricultural or brownfield land and coastal areas or ocean surfaces, thereby capturing and storing carbon. EW could improve soil quality and help counteract ocean acidification. An extensive infrastructure, however, would be required. Moreover, mining & grinding requires low-carbon energy sources and could have other environmental side effects, such as air and water pollution. Technical status: research; Potential in 2050: up to 4 Gt CO_2/year; Permanence: high; Costs: USD 50-200/t.

Table 2 provides an overview of the NETS and allows for a comparison of various options along the dimensions highlighted above.

[11] Biochar is related to soil carbon sequestration and is sometimes grouped together with SCS under "land management". It requires a substantially different intervention to collect, burn, and distribute the biomass (Jeffery et al., 2020).

[12] To be robust, the quantification should consider emissions from biomass production such as deforestation, use of fertilizers, transport, etc.

Table 2: Summary of NETs

Technology	2050 sustainable global potential ($GtCO_2$/y)	Costs across literature (US/tCO_2)	Technical status	Permanence	Benefits beyond CDR	Potential negative effects
Afforestation & reforestation (AR)	0.5 – 3.6	\$2 – 150	Existing	Vulnerable	Soil fertility, biodiversity	Food security, biodiversity, albedo
Soil carbon sequestration	Up to 5	\$45 – 100	Existing	Vulnerable	Soil fertility, water, biodiversity, food security	Possible increase of N_2O
Biochar	0.5 – 2	\$30 – 120	Demonstration	Vulnerable	Soil fertility, water, possible decrease of N_2O	Food security, biodiversity, release of methane if used in rice paddy soils
BECCS	0.5 – 5	\$15 – 400	Demonstration	High	Energy, (CO_2 use)	Food security, biodiversity, air pollution, possible increase of N_2O
DACCS	0.5 – 5 with constraints Up to 40 without	\$30 – 1000	Demonstration/ commercial	High	(CO_2 use)	Energy requirements
Enhanced weathering	2-4	Large variation	Research	High	Soil amelioration, nutrient source	Ground/ water pollution, mining and extraction, air pollution

Source: Adapted from (EASAC, 2018) and (Minx et al., 2018)

3.3. Policy considerations for supporting NETs

The NETs reviewed above differ significantly in terms of their technological status, costs, potential scale and permanence. They can also trigger positive and negative side effects, which can help or hinder progress towards sustainable development goals. Removals through natural approaches, for example, may provide significant co-benefits in the form of increasing biodiversity and through the provision of greater ecosystem services but may induce competition for agricultural and wild, unmanaged land. Accordingly, a diverse set of instruments, operating on supply and demand-side factors, are required to ensure that the right incentives are in place for the NETs' R&D and deployment (Nemet et al., 2018). These instruments must also account for both the positive and negative side effects the NETs may have for a broader set of objectives than reducing climate change, such as biodiversity loss, energy and food security, etc.

The next three sections provide an overview of the considerations relating to these instruments under three headings. First, for those NET options in Table 2 whose technological status is research or demonstration, *support for R&D* is crucial. This ensures that removals are produced using a portfolio of technologies, which could then supply a market for RUs that generates a revenue stream for the operation of NETs. Second, the RUs themselves must be certified by a robust mechanism such that each unit corresponds to the permanent removal of a ton of GHG from the atmosphere. Although there is some experience from existing offset programs, particularly in relation to credits from afforestation projects, new mechanisms for *the certification and governance of RUs* specific to the NET context must be developed. Third, the existing demand by private sources for RUs is inadequate to achieve the scale of NET deployment required to meet the Paris Agreement targets. Therefore, *government support for the deployment of NET options* at scale is required to create additional demand for the RUs.

3.3.1. Support for R&D

Support for basic R&D on NETs is a low-regret option because the scale of removals required during this century necessitates the joint deployment of several NETs – many of which are in the research and demonstration stage. Such support is also well-justified because knowledge has several features of a public good: once available in the form of an idea, it is difficult to exclude others from using it. This makes it difficult for the originator of the idea to capture the full benefits from the innovation itself, as well as from new ideas and innovations the idea stimulates. Consequently, there is typically less investment in R&D than would be in the best interest of society.

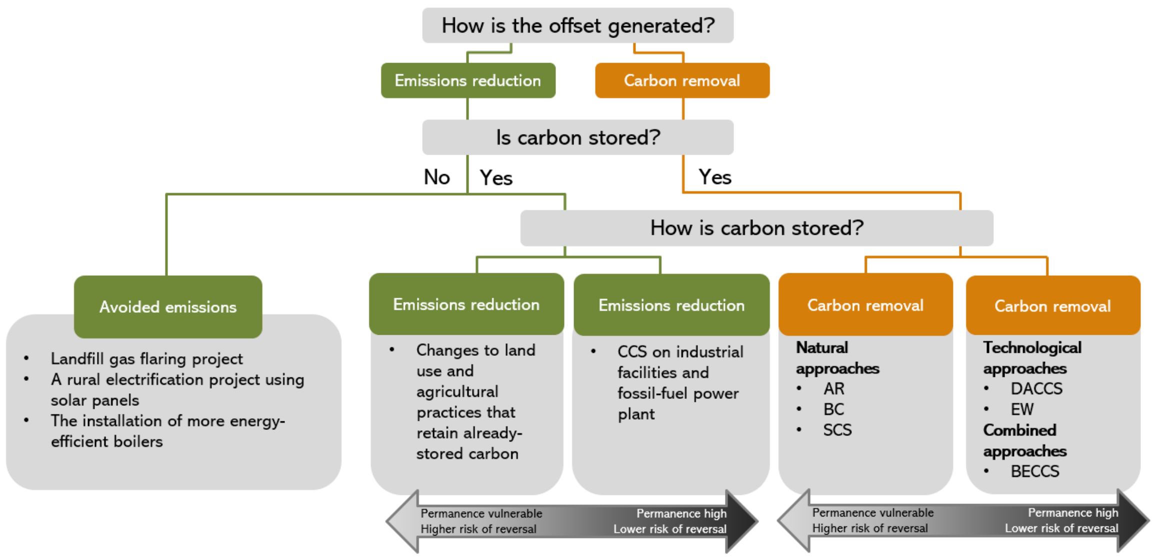
Existing government programs to support basic research to incentivize environmental innovation through universities, research councils, and design competitions have been studied extensively and found to be broadly effective (Popp, 2019). In the specific context of CDR from NETs, there have been calls in the EU for increased investment in R&D (Geden & Schenuit, 2020). Fiscal incentives for R&D activities through the provision of tax breaks can also deliver promising results. Applying the lessons learned from these programs to support R&D on a range of NETs can lay the foundation for the eventual large-scale deployment of removal activities.

3.3.2. Certification, MRV and governance of removal units

RUs are the foundation of a market where CO_2 removals are treated as a product that generates a revenue stream for their producers. The existence of a robust certification mechanism for generating high-quality RUs, including measures for ensuring the permanence of removals, is thus important for all NETs (the latter element being particularly important for NETs that rely on biological sinks due to reversal risks). This section briefly addresses design elements in the generation of such units.

Here it is also important to clearly differentiate between *RUs* and current *offset credits*. As outlined above, negative emission technologies entail the capture *and* storage of carbon. Specifically, the activity must result in an *overall reduction in atmospheric concentrations* – such that GHGs that had previously been in the atmosphere are physically removed from the atmosphere and permanently stored (taking into account lifecycle emissions and the counterfactual baseline of what would have occurred in the absence of the intervention). This is in contrast to most of the offset credits available to date, which are often based on *reducing emissions* below an established baseline. A landfill gas flaring project, for example, can *reduce* the volume of emissions that is released into the atmosphere, but will not *remove* emissions that had previously been in the atmosphere. RUs can thus be treated as a subset of offset credits, and not all offset credits are RUs. See Figure 4.

Figure 4: Taxonomy of carbon offsets



Source: authors' elaboration based on University of Oxford (2020) and UNEP (2017)

In many ways, the design of a mechanism to certify RUs mirrors that of designing a program for the certification of offset credits:

- *Technological scope* (what types of NETs should be eligible to generate RUs?): Policymakers may wish to ensure that technologies eligible to produce RUs render themselves to conservative quantification of emission removals and are permanent (and/or there is a robust mechanism to address non-permanence – see below). One challenge particular to the generation of RUs is the treatment of options that are prone to saturation (such as forestry and soils), as policymakers may not be agnostic as to when or how these technologies should be tapped into. Co-benefits and adverse effects may also play an important role in the decision of technological scope, as well as the supply potential of the technology and speed of removals (e.g. DACCS may be faster to absorb CO_2

than forests). Technological scope is thus not only a matter of technical feasibility, but also relates importantly to the societal choice on decarbonization pathways.

- *Geographical scope* (where should the credited activities be located?): Removal activities could be located domestically and/or abroad. This includes considerations of the geographic place of both co-benefits and risks; domestic storage potential; implied international financial flows; and international accounting.[13]
- *Governance* (who should govern the certification mechanism?): Governance can be domestic, supranational (e.g. in the case of the EU), international (e.g. a supervisory body under Article 6 of the Paris Agreement), or by another third party (such as an independent certification programme like the Gold Standard or Verra). Governance can also be mixed, e.g. if a national body relies on an international body for the development of quantification methodologies.

After establishing the main scope and governance considerations, several rules and processes must be put in place to make sure that RUs are additional[14], permanent[15], conservatively quantified, and that RU transactions are tracked so as to avoid double-counting. (Schneider & La Hoz Theuer, 2018)

Quantifying the results of removal activities and ensuring their permanence entails challenges that are specific to the particularities of NETs and the response of the climate system to the differences between emissions and removals. The elements below are based on the several challenges identified by Brander, Ascui, Scott, & Tett, (2021):

- *Quantifying total changes in emissions and removals through the use of NETs over time*: This includes how to quantify life-cycle changes vis à vis a counterfactual baseline of emissions and removals[16]; how to take into account indirect effects (such as indirect land-use change caused by increased market prices for biomass); and accounting for the distribution of emissions and removals over time[17], among others. It will be important, for example, to set robust criteria to ensure that biomass – e.g. for use in BECCS – is sustainable.
- *Dealing with non-permanence*: This includes accounting for (planned and unplanned) reversals in individual stores of CO_2 (such as reductions in forest cover and leaks from geological storages); dealing with uncertainty in the risk of future non-permanence; and ascribing liability in the case of

[13] Fyson et al (2020), for example, estimate that a cost-optimal and fair distribution of CDR effort across countries would entail the international transfer of CDR outcomes of up to 500Gt until 2100.

[14] Additionality refers to whether the mitigation action would have occurred in the absence of the incentives from the crediting mechanism.

[15] While the IPCC Glossary does not contain a definition for permanence, Assessment Report 5 outlines non-permanence: “Non-permanence / reversibility: Reversals are the release of previously sequestered carbon, which negates some or all of the benefits from sequestration that has occurred in previous years. ” (IPCC, 2014, Chapter 11.3.2)

[16] A counterfactual baseline is necessary because even though carbon stocks following the implementation of a NET might increase over time, this does not necessarily mean that the NET has not caused a decrease in removals (or increase in emissions) relative to what would have happened in the absence of the intervention (Brander et al., 2021).

[17] For example, in the case of a planted forest, this would entail the quantification of emissions related to planting, harvesting and biomass transport, in addition to the annual removals for forest growth. Here, it is important to note that while the project over its entire lifetime may have a net removal result, it could nonetheless have high emissions in the beginning of its operation, therefore creating a ‘carbon debt’ that could take several decades to be compensated for through forest growth.

non-permanence. Options to mitigate the risk of non-permanence include reducing the risk of non-permanence (e.g. by excluding activities with a higher non-permanence risk); requirements for the monitoring and verification of permanence; and establishing compensation requirements (liability) in the case of reversals (e.g. buyer liability, seller liability, and/or a pooled buffer approach) (Schneider, Conway, Kachi, & Hermann, 2018a). Other avenues, such as the ton-year quantification approach, have also been proposed (IPCC, 2000, Chapter 2.3.6).

- *Non-equivalence of 'No overshoot' and 'Overshoot and removal' pathways*: A key challenge in using removals to compensate for emission overshoots is that the cooling effect of each RU after an emissions overshoot may be smaller than the warming effect of a prior positive emission (Zickfeld et al., 2016).

The various risks identified above could also be addressed through discounting, i.e. by departing from a 1:1 equivalence between emissions and (ex-post) removals. The discount could be applied either at the generation of RUs (such that each RU is already risk-discounted) and/or at the use of such RUs. Meyer-Ohlendorf (2020), for example, argues that emissions and removals differ in terms of climate protection, monitoring and enforcement, and suggests that very high (e.g. 10 to 1) discount factors at the use of such units might address this problem. The need for and the level of discount factors would require further research.

It is also conceivable that different types of units (with different rules and requirements) be generated for different risk profiles or technology types.[18] Different units could then also be subject to different rules on their use.

Another challenge related to the certification of RUs pertains to complexities in the value chain of RU generation. For example, in the case of BECCS, the biomass could be grown in country A, the biomass could be combusted and the CO_2 captured in country B, and the storage of the sequestered CO_2 could take place in country C. A question of property rights thus arises: who should be awarded the RU? This question also has ties to methodologies for national inventories as well as to international accounting under Articles 6 and 13 of the Paris Agreement. It could make sense to reflect the physical processes wherever they happen – e.g. the activities in country A could be awarded the removal (since this is where the CO_2 is captured from the atmosphere by plants), country B would have no emissions (assuming it all gets captured), and country C would be responsible for any CO_2 leaks in its territory, while receiving payment for its storage services. In order to demonstrate the removal, an ETS-covered BECCS installation in country B could then purchase the RU from country A at the same time that it acquires the biomass. Complexities in the value chain of RU generation can also arise where all activities take place in the same country, but where some activities are covered by the ETS and others are not. Such questions merit further research.

While important challenges exist in robustly certifying removals, several jurisdictions have examples that can be built upon, such as New Zealand's generation of units for forestry activities in the NZ ETS, Québec's generation of offset credits[19], California's generation of forest offsets, California's CCS protocol, the EU CCS

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[18] Under the Clean Development Mechanism, for example, AR projects generate special units – lCERs and tCERs – which must be replaced by the host country with permanent Kyoto units at the end of the (last) crediting period, regardless of whether a reversal occurred (Schneider, Conway, Kachi, & Hermann, 2018b).

[19] The Quebec draft forest offset protocol, which makes use of the tonne-year quantification approach, is available on the program's webpage (Québec, 2020).

framework, and the Australian Emission Reduction Fund, among others. The EU is also working on an EU carbon removal certification mechanism, details of which are yet to be fleshed out.

3.3.3. Support for deployment of NET options

Currently, private demand for RUs is almost exclusively driven by voluntary offsetting decisions of private citizens and firms.[20] It is orders of magnitude smaller than the volume of removals required to meet the Paris Agreement targets.[21] The underlying reason for the inadequate demand is the fact that climate change is an externality. Just as GHG emitters have no direct incentive to reduce their emissions without climate change policy, nor do citizens and firms have a direct incentive to purchase removals in order to reduce climate change. Therefore, once the technological readiness level of an NET increases beyond R&D stages and the technology approaches commercialization, policies could focus on ensuring there is sufficient demand in the market, providing a revenue stream for the operators of NETs and allowing them to scale up their operations. The increasing scale of operations can also help drive down costs by encouraging learning-by-doing, much like the drop in the renewable energy costs observed following the deployment of support provided through renewable obligations, feed-in-tariffs and preferential grid access, among others.

Focusing on the identity and motivation of the sources of demand in the market for RUs helps illustrate the policy considerations which arise in the context of supporting deployment. At one extreme, a government may directly purchase RUs through public procurement/tenders paid for using general revenues to, for example, comply with its domestic or international targets. To determine the "right" price for these purchases the government may use reverse auctions where all or a subset of NETs are eligible to submit bids. Alternatively, the government may offer to buy at a pre-announced price (like feed-in-tariffs for renewable energy projects) or offer other fiscal incentives.[22] The magnitude of these incentives may be guided by the existing carbon prices in the jurisdiction, including carbon taxes, allowance prices in an ETS, and/or social cost of carbon estimates the government uses in environmental impact assessments. An important margin to consider in this respect is whether the government is willing to purchase from non-domestic sellers. The key advantage of this approach would be that the government can determine the scale of the removals procured through this market and provide a dependable source of demand for removals. The scale, in turn, determines the fiscal cost of this approach which is its main disadvantage because it commits government resources to NETs support which could be deployed elsewhere.[23]

At the other extreme, the government could take a hands-off approach and let the private sector provide the only source of demand in the market for removals. Citizens who are concerned about their carbon footprint and businesses pursuing corporate social responsibility goals already purchase offsets for voluntary purposes. Indeed, a recent analysis finds that among the world's 2,000 largest listed companies, about one fifth has made a made a net zero commitment (Black et al., 2021). This is likely to create demand for RUs as these companies move to meet their targets. The fiscal cost of this approach is negligible, as even the certification and governance of RUs may conceivably be left to the private sector and the government's responsibility is limited

[20] Unit demand from CORSIA is not expected to pick up until a few years into the future.

[21] Voluntary offset transaction volumes are approximately 100 $MtCO_2e$ in 2019 and 1200 $MtCO_2e$ since 2005 (Forest Trends' Ecosystem Marketplace, 2020). Note that not all offset credits are RUs as discussed above.

[22] The federal "Tax Credit for Carbon Sequestration" is particularly prominent example for fiscal incentives from the US.

[23] The government can reduce the fiscal burden of this approach by selling the RUs it has acquired to hard-to-decarbonize sectors. See Section 4 for a more detailed discussion of this in the context of an ETS.

to applying the commercial laws and regulations which include ensuring that the transactions in this market are not fraudulent and market power that may exist on either side of the market is not abused. Unlike public procurement, however, the government has no influence over the volume of transactions in this market. As mentioned above, this will never lead to a removals market that can deliver the scale of removals required for meeting the Paris Agreement targets.

In between these two extremes are several hybrid options. The government can mandate removal obligations for private citizens, but this could have undesirable consequences for distributional outcomes, equity and justice. Placing those obligations on firms (similar to Renewable Obligations in the UK)[24] could be an alternative but devising a suitable allocation mechanism is challenging and would likely be strongly contested. The government can realign public procurement towards climate-neutral suppliers who must demonstrate their neutrality by offsetting their emissions using RUs. A connection between the market for RUs and any existing carbon pricing instrument can also be created. For example, the government can accept RUs against carbon tax liabilities, although doing so would mean foregoing revenues that could otherwise be collected.

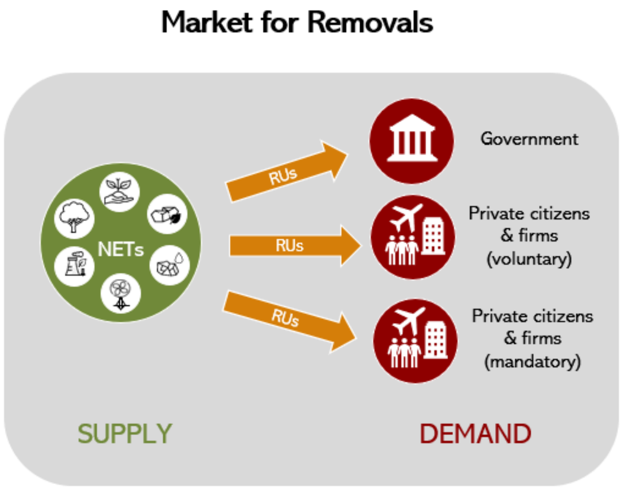
Similarly, making RUs fungible with allowances in an ETS, or making it possible for them to be used for compliance under qualitative or quantitative restrictions, could support NETs' deployment. Emitters, for example, could be required to submit an allowance for burning fossil fuels and receive a RU for the emissions they capture and store while remaining liable for their net emissions. The government can go even further and offer a temporary premium on the carbon price in the ETS (like feed-in-premiums for renewable energy) to ensure that emerging technologies receive some support without providing perverse incentives and making them reliant on continued support for commercial viability. Alternatively, or in addition, the government may offer carbon contracts for difference (CCfD) to reduce or remove the risk associated with carbon price variability by guaranteeing a minimum or fixed carbon price over the life of the contract. CCfDs can be especially helpful for NETs with a large upfront cost and payback over a long-time horizon.[25] However, creating these connections between allowance and removal markets may be viewed as diluting mitigation incentives in the ETS. It also has implications on potentially reduced allowance auction revenues and greater government spending. Section 4 explores several possible models for the connection between the ETS and the market for removals.

The policy considerations outlined in Sections 3.2.1-3.2.3 can be viewed in the context of Figure 5, representing the market for removals. On the supply side, various NET options produce RUs using technology options which differ in market readiness, cost and scalability. Providing support for R&D can, therefore, help with putting a reliable supply in place to meet the small but growing demand for RUs. The demand side can include direct purchases by the government, voluntary measures by private citizens and firms, as well as mandatory removal obligations established through regulation. Both forms of government intervention call for a robust certification and governance mechanism which must clearly and credibly establish what a RU is.

[24] See https://www.ofgem.gov.uk/environmental-programmes/ro/about-ro

[25] For a related method which uses auctions to reduce price risk, see the World Bank's Climate Auctions Program at https://www.worldbank.org/en/programs/climate-auctions-program.

Figure 5: The market for removals



Source: authors' own elaboration

Figure 5 is also helpful in exploring the myriad of issues and questions that arise in the context of how the relationship between the market for removals and ETS can be structured. This topic is addressed in more detail in Section 4.

4 Options for interactions between ETSs and removals

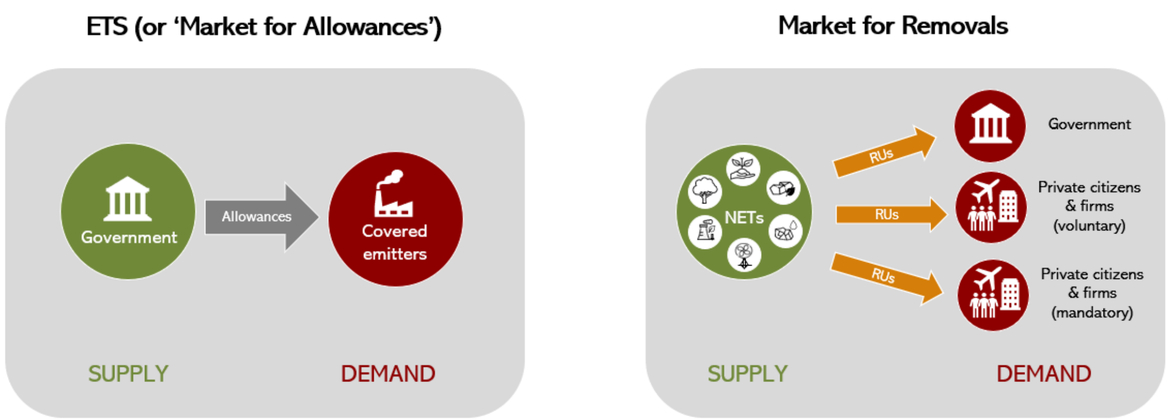
The market for removals described in Section 3.3.3 can interact in different ways with an ETS (or market for allowances – see Figure 6), depending on the direct or indirect connections the government may create between them as well as differences in the price of allowances and RUs. This section explores the potential interplay between ETSs and removals in further detail. For simplicity of depiction, we present here a highly stylized ETS without offsets or linking, without allowance demand by financial actors or for voluntary cancellations. Removing these simplifications would not affect the conclusions presented below.

It is assumed that RUs are generated by a robust certification mechanism, and, therefore, represent real and permanent removals with each RU representing the removal a ton of CO_2 from the atmosphere regardless of the NET behind it or location of the removal. The various models presented below could be combined with the alternative options discussed in Section 3.3.2, such as discount factors in the use of RUs and employing different units (and corresponding rules) for different technologies or risk profiles. For simplicity, however, in this section it is assumed that all RUs are equal.

Moreover, the focus of the section lies primarily on ETSs and their interaction with the market for removals. It is important to highlight that residual emissions may exist not only within the ETS, but also outside of it (notably emissions from agriculture, which is likely to stay outside the scope of many ETSs). Countries with net zero or net negative targets would likely require the use of removals to compensate for residual emissions and overshoots both within and outside the ETS.

Table 3 provides an overview of the characteristics of both markets.

Figure 6: Two markets



Source: authors' elaboration

Table 3: Allowance and removal markets: comparison

	ETS	Market for removals
What is being traded?	Right to emit 1 tCO_2e into the atmosphere	Certificate which guarantees 1 tCO_2 has been removed permanently from the atmosphere
Who is supplying it?	Government	Removers using NETs
Who is demanding it?	Covered emitters	• Government (potentially) • Private citizens and firms (voluntary) • Private citizens and firms (mandatory)

Source: authors' elaboration.

The sections below describe and discuss four generic models of the possible relationships between the ETS and the removals market. The models are deliberately stylized – hybrid or in-between approaches are also possible. The models, moreover, are not mutually exclusive – the same jurisdiction could employ more than one model at any point in time.

The analysis compares the models across several criteria:

- *Control over abatement and removal pathways*: the extent to which the model allows for government control over the balance between abatement and removals in ETS-covered sectors.
- *Avenues for incentivizing NETs*: whether and how the ETS allows for the incentivization of NET development and deployment, also in the context of large price differentials.
- *Compensation of residual emissions and flexibility on ETS cap setting*: whether the model provides an avenue for the compensation of residual emissions (and trajectory overshoots) and, consequently, whether or not there is flexibility in setting a positive, zero or negative ETS cap.
- *Contribution to cost-effective price discovery*: as emissions approach zero, challenges in the ETS may arise with regards to liquidity and market power. Also, the introduction of RUs can have impacts on the allowance price and expectations thereon.
- *Fiscal balance*: balance of revenues and expenditures by the regulator related to emissions covered by the ETS and removals, where government expenditures are for the purchase of RUs, and revenues are derived from allowance auctions (if applicable) and sales of RUs (if applicable).
- *Administrative burden*: Relates to the additional burden on the government from administering the system, e.g. where the responsibility of purchasing RUs falls on the government.

The criteria above are interrelated and contribute to various aspects of policy effectiveness, cost efficiency, political resilience and administrative feasibility. Control over pathways and flexibility in cap-setting, for example, can be key in ensuring the effectiveness of an ETS as a policy measure to help achieve jurisdictions' net zero targets. Issues of price discovery and avenues for incentivizing NETs are important in the cost-effectiveness of ETSs specifically and of deep decarbonization in general. Issues of fiscal balance and of compensation for residual emissions can play an important role in political resilience of the ETS over time. It is important to note that the analysis below focuses primarily on the question of "if" and "how" ETSs could interact with a market for RUs. Another important question relates to "when" this could or should happen. As highlighted in the final chapter, the wide-ranging potential impacts of such interactions call for caution and careful analysis before effecting large policy changes in ETSs.

4.1. Model A: Disconnected markets

In Model A, the ETS and the removals market are completely disconnected. This means that the ETS does not make use of any RUs. Such units, however, could be used outside of the ETS. Figure 7 portrays the two markets, with the 'wall' between them illustrating the separation.

Figure 7: Model A : Disconnected markets

Source: authors' elaboration.

4.1.1. Model A: opportunities

Total control over abatement and removal pathways: By keeping the two markets separate from each other, the incentives for abatement under the ETS are kept distinct from the incentives for removals. This is in line with recent studies that urge policy makers to keep abatement and removal targets separate from each other (McLaren et al., 2019). The separation can also provide more long-term certainty for investors in abatement technologies under the ETS, who will not be exposed to the risk that their investments in GHG abatement are rendered unprofitable by the availability of cheaper removal options in the future. Such a separation would also prevent a situation where current investors over-rely on the future availability of removal options and lock themselves into high-carbon trajectories. Government support programs for NETs could be disconnected from the ETS allowance price, possibly reducing the price uncertainty for NETs as compared to e.g. Models C and D.

4.1.2. Model A: constraints

Restricted avenues for incentivizing NETs: Under Model A, the ETS would not be able to directly incentivize NETs through the purchase of RUs. Nevertheless, the ETS could still contribute to the incentivization of NETs through the carbon price (primarily by incentivizing the development and deployment of CCS technologies under the scope of the ETS) and by using auction revenues e.g. in funding NET research, development and deployment (RD&D) activities. It may be worth noting, however, that as the cap approaches zero, auction revenues are also likely to fall, thus affecting the availability of resources.

No compensation of residual emissions within the ETS and no flexibility in cap-setting: Under Model A there would be no compensation avenue for residual emissions under the ETS. Consequently, the ETS cap would likely need to remain positive to allow for residual emissions from activities that are valuable, but for which abatement technologies are either not available or too costly. To achieve aggregate net zero emissions, under Model A these residual ETS emissions would then need to be compensated for through the use of RUs acquired independently of the ETS.

Challenges to cost-effective price discovery as the cap approaches zero: As emissions approach zero and the number of market players shrinks, issues of market liquidity and uneven market power could become a problem under the ETS. This will, to some extent, also be impacted by the ETS scope and the policy choices regarding residual emissions from the ETS sectors – and, therefore, the degree to which the cap approaches zero.

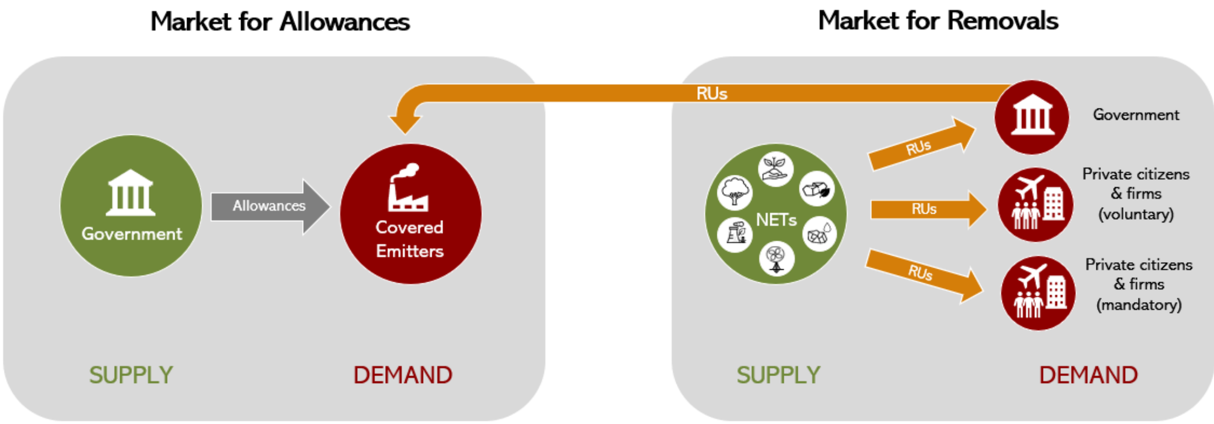
Potential high government expenditure for the acquisition of RUs and corresponding administrative burden: Insofar as the government aims to make use of RUs outside of the ETS (e.g. to achieve net zero targets in the context of residual emissions), and if the responsibility for the purchase of these units falls on the government itself, this could entail an increase in expenditure by the government, as well as significant administrative burden. These costs could be financed through general government revenues and/or through ETS auction revenues, noting that the availability of auction revenues would be impacted by the cap trajectory over time.

4.2. Model B: Connected through government

Under this model, the two markets are connected through the government, who buys RUs in the removal market and introduces them in the ETS. The quantity of RUs that flows into the market would be controlled by the government, and the regulator could also determine who can use RUs and when. See Figure 8.

RUs could be used within the ETS in various ways, e.g. through free allocation to entities at risk of leakage, as a source of units for price containment reserves, as emissions compensation for hard price ceilings, and/or as extra allowances for auction.

Figure 8: Model B: Connected through government



Source: authors' elaboration

4.2.1. Model B: opportunities

Control over abatement and removal pathways: Since the use of RUs is controlled by the government, Model B maintains government control over how many (and where) RUs are used. With this, the government can exercise control over decarbonization pathways and over the balance of abatement and removals in the net zero target.

Avenue for incentivizing NETs, also in the case of price differentials: Model B allows the ETS to act as a source of demand for RUs. Importantly, since RU flows are intermediated by the government, this option offers a possibility for government financial support beyond the market price of allowances, which can be important particularly in the case of large differentials between the allowance price and the costs of generating RUs (see section 3.3.3). Model B thus offers an opportunity to help guarantee the sale of RUs at a financially sustainable price for NET operators, supporting the deployment of these technologies - many of which, as seen in Section 3.2, have costs several times higher than current allowance prices. Large-scale deployment facilitated through government support could facilitate cost reductions over time. Model B, moreover, allows for differentiated government treatment of different technologies and their respective costs – thereby enabling more targeted support. Purchasing RUs for prices higher than allowance prices, however, would entail a negative impact on the fiscal balance as elaborated further below. (Under such price differentials, moreover, the trade in RUs within the ETS would also depend on the regulator selling RUs within the ETS at a discount vis à vis the price paid for such units.) The purchase of removals in large quantities could also provide additional certainty to RU producers and, possibly, reduce transaction costs.

Avenue for compensation of residual emissions within the ETS; flexibility in cap-setting: By allowing for the direct use of RUs within the ETS, Model B establishes an avenue for compensating residual emissions within the system, while retaining regulator control over how many, and where, RUs are used. With this, the ETS cap can now be either positive, zero or negative, with more opportunities for compliance cost containment. Ultimately, the use of RUs in the ETS will depend on the ETS cap and on the price differentials between the ETS and the removals market.

4.2.2. Model B: constraints

Impact on price expectations; limited improvement of price discovery dynamics as caps near zero: the introduction of RUs into the ETS could impact the market price and expectations thereof. This relates to expectations and uncertainties by market players both about the costs of producing RUs and their availability, as well as about the volume of RUs that will be allowed by the regulator under the ETS over time. Regulatory uncertainties could be managed by clear and transparent rules surrounding when the regulator injects RUs into the allowance market. Moreover, Model B provides only limited respite to the issues of market liquidity and market power under the ETS when emissions approach zero, due to the limited number of market players.

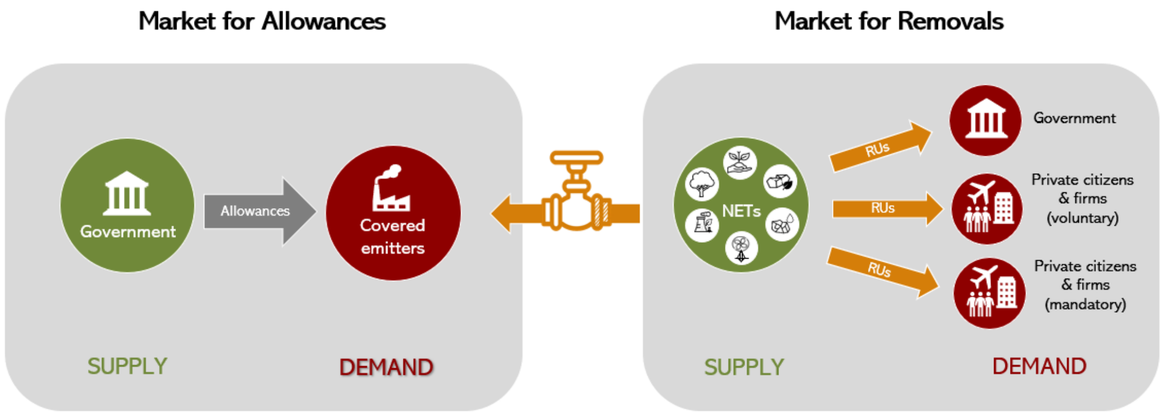
Government expenditure for the acquisition of RUs, with avenue for revenue-raising through sale of RUs under the ETS: Under model B, RUs are first purchased by the government and then – possibly – re-sold in the ETS. The fiscal balance for the regulator would thus depend on the price paid for RUs in the removals market, on whether RUs are sold by the regulator under the ETS and for what price, and on price impacts (such as decreased auction revenues) due to the higher availability of units under the ETS.

Administrative burden: Similarly to Model A, Model B sees a high administrative burden on the regulator for the purchase of removals. Model B also has a higher dependence on centralized government policy and action on the purchase of RUs.

4.3. Model C: Connected with restrictions

Under Model C, the allowance and removal markets are directly connected, through transactions between ETS-covered entities and removers. Under this model, the government no longer acts as the intermediary that brings RUs into the ETs but can still place qualitative and quantitative limits on the transactions between the two markets, similar to those that have been applied to the use of offsets (*EMISSIONS TRADING IN PRACTICE: A Handbook on Design and Implementation*, n.d.; Chapter 8). See Figure 9.

Figure 9: Model C: Connected with restrictions



Source: authors' elaboration

4.3.1. Model C: opportunities

Control over pathways: As the use of RUs under Model C would be subject to rules and limits, there would still be government control over how many RUs are used – and, consequently, over decarbonization pathways. Rules could also specify how and by whom these units could be used.

Avenue for incentivizing NETs: Model C allows the ETS to act as a source of demand for RUs, although the size of such an incentive will depend on the ETS cap and on the price differentials between the ETS and the removals market.

Avenue for compensation of residual emissions within the ETS; flexibility on cap-setting: Similarly to Model B, Model C offers a compensation avenue for residual emissions in the ETS, and there is, therefore, flexibility on the cap being positive, zero or negative while offering cost containment options.

Improved price discovery as the cap approaches zero: The integration of generators of RUs into the ETS may make the ETS more liquid and reduce concerns of uneven market power as emissions under the ETS approach zero.

Improved fiscal balance and reduced administrative burden for the regulator: Under Model C, the government would no longer be the primary channel for the purchase of RUs for use under the ETS. Model C is thus likely to have a more favorable fiscal balance for the regulator than models A and B. The fiscal balance would depend on the ETS cap, on the volume of allowable RUs in the ETS, and on whether the government would be required to purchase RUs outside the ETS to compensate for any residual emissions that remain under the ETS after provisions for purchasing RUs by covered entities have been exhausted.

4.3.2. Model C: constraints

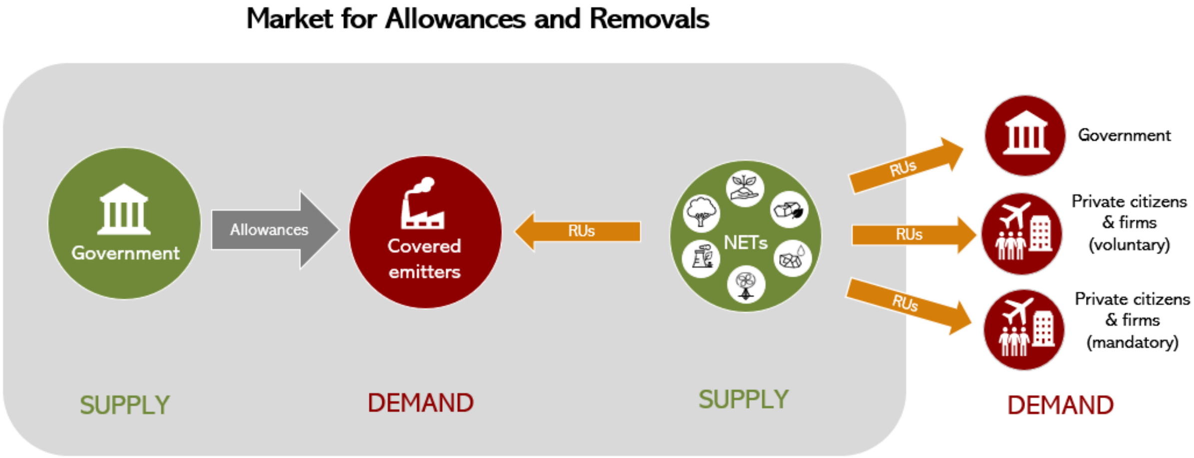
Limited avenue to incentivize NETs in case of price differentials: Covered entities would only have the incentive to purchase removals if the cost of doing so was comparable to the cost of purchasing allowances. In addition, the NETs would face the price risk in the ETS in Model C, which could undermine R&D and deployment incentives. Therefore, this model provides limited opportunity to support NETs through the ETS if RU generation costs exceed the abatement costs under the ETS. That said, the regulator could complement the incentives generated by the ETS with a CCfD in order reduce the risks associated with price variability and differentials, but thereby increasing the fiscal burden for the regulator.

Impact on price expectations: Similarly to model B, under model C the introduction of RUs into the ETS could impact the price (and expectations thereof) under the ETS. This relates to expectations and uncertainties both about the costs of producing RUs and their availability, as well as about the volume of RUs allowed under the ETS over time. This effect is likely to be stronger in Model C than in Model B.

4.4. Model D: Integrated markets

Under Model D, emitters and removers are part of the same market. This means that the government would issue allowances or credits to removers (e.g. as currently done in New Zealand). Importantly, under Model D there is no limitation on the number of RUs that can be used in the ETS, although the regulator could determine which technologies are integrated into the ETS. Removers can, nevertheless, still sell RUs to actors outside of the ETS. See Figure 10.

Figure 10: Model D: Integrated markets



Source: authors' elaboration

4.4.1. Model D: opportunities

Avenue for incentivizing NETs: Model D allows the ETS to act as a source of demand for RUs, although the size of such an incentive will depend on the ETS cap and scope (and, consequently, on the potential demand for removals) and on the price differentials between the ETS and the removals market.

Avenue for compensation of residual emissions within the ETS; flexibility on cap-setting: Similarly to Models B and C, Model D offers a compensation avenue for residual emissions in the ETS, and there is, therefore, flexibility for the regulator on the cap being positive, zero or negative while offering ample cost containment options.

Improved price discovery as the cap approaches zero: The integration of generators of RUs into the ETS may make the ETS more liquid and reduce concerns of uneven market power as emissions under the ETS approach zero. Such a market could provide for more cost-effective price discovery than the one under Model C. On the other hand, an unconstrained inflow could increase uncertainty (see 'constraints' below) and detract from price discovery.

Improved fiscal balance and reduced administrative burden for the regulator: As in the case of model C, under Model D the government would no longer be the primary channel for the purchase of RUs for use under the ETS. The absence of limits on the use of RUs means that Model D is likely to have a more favorable fiscal balance for the regulator than all other models, although this will depend on price differentials between the two markets and the impact on e.g. allowance auctions.

4.4.2. Model D: constraints

No government control over decarbonization pathways within the ETS: with the absence of restrictions on the use of RUs in the ETS, the government will not be able to guide decarbonization pathways in terms of choices on abatement vs removals. Regulated entities could risk facing an effective allowance price ceiling imposed by removal costs of eligible NETs, which could delay investments in mitigation and lead to a high-emissions lock-in, which could in turn make long-term targets more expensive to reach (Vogt-Schilb & Hallegatte, 2014). Altogether, this is likely to lead to a high dependence on removal technologies for decarbonization pathways.

Limited avenue to incentivize NETs in case of price differentials: A direct connection between the ETS and the removals market would mean that the RU price would be no greater than the allowance price. This provides limited opportunity to support NETs through the ETS if RU costs exceed ETS market prices. Here again, CCfDs could provide an avenue of additional support by the government, complementing the incentive from ETS demand but increasing the fiscal burden for the regulator.

Likely limitation to domestic removals: Model D is unlikely to apply to international removers, as it seems unlikely that such international entities could be regulated under the ETS.

4.5. Models A-D: summary

Table 4 below provides a summary of the features presented above.

Table 4: Summary of models A-D

	Key features	Opportunities	Constraints
Model A: Disconnected markets	• Allowance market (i.e. the ETS) and removal market are completely disconnected	• Incentives for emission reductions under ETS are separated from the incentives for removals – government support for NETs can take place outside the ETS • ETS can still contribute to the incentivization of NETs through carbon price and revenue use	• Can't use ETS to incentivize NETs more directly by purchasing RUs • No compensation avenue for residual emissions in ETS; cap would likely need to stay positive • As the number of market players shrinks, market liquidity & power can become problems • Acquisition of RUs can be costly for the government
Model B: Connected through government	• Allowance and removal markets are connected through government • Quantity of RUs that flows into the market is controlled by government • RUs can be used within ETS in myriad ways (reserves, free allocation, in auctions, etc.)	• Government control over how much (and where) removals are used • Possibility for government financial support to NETs beyond allowance market price, which is relevant in case of large price differentials • Compensation avenue for residual emissions within ETS; cap can be positive, zero or negative	• Potential impacts on market price (or expectations thereof) • As the number of market players remains limited, market liquidity & power can become problems • Can be costly for the government (with cost reduction if RUs are auctioned)
Model C: Connected with restrictions	• Allowance and removal markets are connected directly, through transactions between ETS entities and removers • Government can place limits on the transactions between the two markets	• There can still be government control over how much (and where) removals are used • Avenue for incentivizing NETs • Compensation avenue for residual emissions in ETS; cap can be zero or negative • Improved price discovery as the cap approaches zero • Improved fiscal balance for the government	• Limited avenue to incentivize NETs in case of price differentials, although additional support (e.g. through CCfDs) could be provided by the government • Potential impacts on market price (or expectations thereof)
Model D: Integrated markets	• Emitters and removers are part of the same market • No limitation on the number of RUs that can be used in the ETS	• Avenue for incentivizing NETs • Compensation avenue for residual emissions within ETS; cap can be positive, zero or negative. • Integration of generators of RUs into market may make it more liquid and reduce concerns of market power as ETS cap approaches zero. • Improved fiscal balance for the government	• No government control over decarbonization pathways within ETS; risk of high-carbon lock-in • Limited avenue to incentivize NETs in case of price differentials • Likely limitation to domestic removals

5 Conclusions and questions for further research

Current decarbonization trajectories rely heavily on removals in the second half of the century; the need to remove 100 to 1000 Gt CO_2e before 2100 represents a massive societal, environmental and technological challenge. The status of development and deployment of non-biological NETs remains incipient and there is urgent need to scale-up. This, however, should happen in parallel with – and not detract from – efforts to rapidly abate emissions. Both abatement and removals are necessary to stabilize emissions and, hence, curtail warming.

The large-scale deployment of removals is connected to a number of tradeoffs, and it is, therefore, key to consider all spheres – economic, environmental, ethical and political - when assessing their use. Ultimately, the level of reliance on removals should be the result of a careful societal debate. Similarly, the many different benefits and risks of the various NETs will call for different necessary safeguards when generating RUs, particularly for technologies with uncertain or variable permanence. How these safeguards are established will dictate the quality and cost of RUs. Appropriate rules, MRV and accounting will also be necessary for all NETs, and a diverse set of instruments, operating on both supply and demand-side factors, will be required to ensure that the right incentives are in place for their research, development and deployment at scale.

The necessity to reach net-negative emissions in the second half of the century begs the question of who will pay for any necessary removals, and how. This entails important discussions of burden sharing across jurisdictions, across sectors within a jurisdiction, and over time. The allocation of removal obligations is an important area of further research and is likely to be a focus of important debates on economic effectiveness, fairness, equity and competitiveness.

ETSs are a key element of the decarbonization toolkit – they cover an important part of current emissions and may also cover an important part of forecasted residual emissions, although residual emissions outside of the ETS (e.g. from agriculture) are also likely to remain. Moreover, experience has shown that long-term targets and cap trajectories can have important implications on the expectations and behavior of market participants. The (possible) connections between ETSs and NETs are, thus, an important area of policy debate for ETSs in particular and for decarbonization strategies more broadly.

The various models on interactions between ETSs and removals explored in this paper have different advantages and disadvantages. The key distinctions revolve around the level of government control over the balance of abatement and removals in the system; the flexibility on cap-setting and how to deal with residual emissions; impacts on the market expectations that could lead to myopic behavior and high carbon lock-in; avenues for additional support for NETs in the case of differentials between allowance and RU prices; and the resulting fiscal and administrative burden on governments aiming to achieve net zero. Ultimately, the use of removals in ETSs should follow from the broader societal decision on the preferred decarbonization pathways and should also take into account the limitations of ETSs in addressing barriers to RD&D as well as the differentials between abatement costs and the costs of removing units at the desired quality. Moreover, the wide-ranging potential impacts of interactions between ETSs and removal markets – notably the potential displacement of technologically accessible abatement action by NETs with high reversal risks – call for caution and careful analysis before effecting large policy changes in ETSs. This raises important questions about limits that may be required in the use of RUs for compliance in existing ETSs; the criteria that need to be applied to RUs before allowing them in the ETS and the prospects of the various NETs to fulfil such criteria.

Whether or not removals are used in and incentivized through ETSs, it is crucial to adequately quantify and certify any RUs that are generated. A robust certification mechanism for generating high-quality RUs and a governance mechanism for ensuring their permanence is important for all NETs. Here it is important to highlight the difference between *RUs* and current *offset credits:* while RUs are a subset of offset credits, a key point that often escapes attention is that not all offset credits are RUs.

Generally, however, there seems to be an important disconnect between the currently low social acceptance of large-scale removals and the high importance ascribed to their deployment among scientific circles. The difficulties in fostering support among the general public for removal technologies (in particular to those involving CCS) contrasts with the level of reliance on those technologies from current projected decarbonization pathways. Public acceptance is higher for solutions perceived to be "natural" (such as those related to forestry and soil carbon), but these technologies face important permanence challenges. This calls for a nuanced discussion on NETs and their contributions going forward.

The analysis conducted in this paper has highlighted several areas of further research. Some of these relate to the responsibility over, and the methods for deploying, removal activities: who should be responsible for acquiring RUs? If the government, then how could this be financed and operationalized? If the private sector and/or individuals, how and on what basis should the obligation be distributed? This becomes particularly critical in the context of large emission overshoots, which would require large volumes of removals in the second half of the century for which no clear financing path is yet available.

Several questions also remain unanswered with regards to the alignment of ETS caps with net zero (or net negative) targets. What does it mean, in practice, to have a zero cap within an ETS? What about a negative one? What provisions would be necessary to transition away from positive caps? What would market dynamics in the ETS look like as emissions near zero?

Each model warrants further elaboration – for Model C ('Connected with restrictions'), for example, further research could aim to understand what restrictions for the use of RUs could foster the twin goals of deep decarbonization and large-scale removals. Moreover, in Models B and C, where unit flows are mediated by the government, central banking methods could be used to modulate the flow, liquidity of and price for removals in the ETS. The models, moreover, are deliberately stylized and are not mutually exclusive – hybrid or in-between approaches are also possible, and the same jurisdiction could employ more than one model at any point in time, e.g. where different models target different technologies. Technologies considered to have too-high reversal risks, for example, could be incentivized through non-ETS methods (Model A), with safe but affordable technologies incorporated into the ETS through direct demand by the ETS (Models C or D), and technologies with high price differentials incentivized through the ETS but mediated by the government, to provide additional support (Model B). Such options merit further research.

Several other specific questions merit further investigation, such as the idea of amending biomass emission factors within ETSs to incentivize BECCS through free allocations (Rickels et al., 2020). Also, in the context of linked or multi-jurisdictional systems, what options exist to incentivize removals through unilateral policies, that may or may not interact with the ETS? Other options not investigated here – such as discounting in the use of RUs and employing different unit types for different technologies or risk profiles – could also be further investigated.

It is also important to note that the analysis contained in this study focused on the questions of "if" and "how" ETSs could interact with RUs; the question of "when" this could take place also merits further consideration. Moreover, this study does *not* aim to advocate for the use of RUs in ETSs. Rather, its aim is to contribute to the still-incipient discussion on RUs by summarizing the state of knowledge, outlining conceptual options and assessing them. It is also important to note that several policy options – unrelated to ETSs – could be employed to incentivize the research, development and deployment of NETs. Further research would be necessary to understand the merits and challenges of different policy options to incentivize NETs.

Many questions in the certification of RUs will also need to be addressed – the quality of the RUs will affect the environmental integrity of any ETS or other policy instrument that makes use of such units. Best practice guidelines could provide a good basis for further work in this area, noting that strict quality requirements are likely to lead to high costs and prices of RUs. In addition to the various challenges related to permanence and to monitoring, reporting and verification of RUs, other challenges include understanding if and under what circumstances CCUS and the use of synthetic fuels could be said to generate a permanent removal; what criteria should be employed to ensure that biomass – e.g. for use in BECCS – can be said to be sustainable; as well as the equivalence between emissions and removals (in particular in the context of compensating for overshoots). Moreover, the possible connections and interactions with the voluntary carbon market should also be explored - what rules could or should be put in place to ensure environmental integrity, avoid double counting and facilitate efficient allocation of capital?

Whether or not RUs are integrated into ETSs, the financing of removals remains highly uncertain, and decisions in this respect entail important considerations of burden sharing across jurisdictions, across sectors, and over time.

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