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COMMENT

A case for promoting negative emission technologies: learning from renewable energy support

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ABSTRACT

To achieve net-zero emissions by mid-century, the removal of carbon dioxide from the atmosphere through negative emission technologies (NETs) will play an integral part. With renewable energy technologies (RETs), there has already been the introduction and expansion of a clean technology that faced similar obstacles as NETs—high up-front costs, limited competitiveness, and low public perception. This article compares NET policy proposals with the lessons learned from RET support. For NETs, the use of R&D support for innovation is unequivocal due to its nascency, yet the demand-pull instrument differs whether NETs are used as an alternative mitigation strategy, as a bridging technology or as a last resort. As an alternative mitigation method, a market-based approach by integrating NETs into emission trading systems is applicable because the use of NETs has no additional environmental benefit compared to abatement. Using NETs as a bridging technology requires restricting the demand for NETs to control the volume, and possibly type of NETs. This can be achieved *via* mandates or auctions. As a last resort, the removal *via* NETs requires heavy state involvement as emission removal constitutes a pure public good. This warrants public procurement or even state-led NET operation.

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Introduction

Remaining within the bounds of a 1.5 °C temperature increase requires rapid decarbonization and carbon dioxide removal [1]. Carbon dioxide removal encompasses technical methods like direct air carbon capture and storage (DACCS), natural solutions like afforestation, or a combination as in bioenergy with carbon capture and storage (BECCS) [2–4].[1] While nature-based removal can substantially lower global temperatures [1], they cannot completely substitute engineered removal using negative emission technologies (NETs)[2] [5], with greater capture and storage potential [6]. However, risks and uncertainties of NETs [6] have nourished their negative perception [7, 8] and stifled public support. Therefore, a cleft between the necessity and capability of NETs remains [9].

For NETs to play their assigned part in decarbonization scenarios, the development and deployment of NETs must be supported. So far, targeted support for NETs is rare [10]: Exceptions are tax credits in the US [11] and Canada [12], and grants in Norway [13], tenders in Denmark [14], and auctions in Sweden [15, 16]. Meanwhile, the debate on policies for NETs is growing, recommending a myriad of instruments like mandates [17], quota schemes [18], price guarantees [19] or carbon pricing [20]. The policy proposals for NETs focus, at large, on single policies [15–17, 20], while comparative approaches lack an evaluation baseline [18] or focused on the phasedown of NETs [21]. The question remains what type or portfolio of policy instruments can be most effective and efficient in supporting the necessary development and deployment of NETs to be applicable on a large scale and drive down their cost.

To answer this question, I argue in this paper that we can learn from the case of renewable energy technologies (RETs), which were and are supported by policy instruments including those proposed for NETs. While there are notable differences between RETs and NETs, there are important similarities that suggest that meaningful conclusions can be drawn from the extensive RET literature. Therefore, this article compares the diverse policy instrument proposals in their ability to

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support the innovation and deployment of NETs to guide policy makers.

The lessons from RETs suggest for NETs that deploying a policy mix of a technology-push and demand-pull policy can effectively induce both innovation and deployment. As NETs mature and become competitive, market-based approaches, like emission trading schemes (ETS) or mandates, can be effective while nascent NETs require heavier financial support through, for example, public procurement or carbon contracts for difference. Likewise, the instrument of choice changes in accordance to the future role of NETs, whether deployed as a mitigation strategy, a bridging technology, or as a last resort. As an alternative mitigation strategy, market-based approaches like integration into an emissions trading scheme (ETS) are applicable but as the role of NETs is restricted as a bridging technology, heavier state involvement through auctions becomes necessary as investment opportunities dwindle, and the removal of emissions gains characteristics of a public good.

This article is set up as follows: First, I compare NETs to RETs to reason the usefulness of RETs as an example. Subsequently, I list the various policy proposals for NETs, contrast them with the lessons learned from RET support, and discuss what this means for NET support. The section is differentiated by instrument: 1) research and development (R&D), 2) fixed and premium payments, 3) mandates, 4) carbon pricing, and 5) policy mixes. Finally, I compare the outcomes across instruments acknowledging the possible future roles of NETs.

Similarities and differences between NETs and RETs

To assess an optimal policy mix to support NET development and deployment in the absence of experience, I draw on the knowledge of RETs. As the instruments proposed for NETs are part of the policy toolbox supporting RETs which have been extensively studied due to the considerable history of RETs.[3] Aside from practical reasons, the similarities between NETs and RETs in their early phase warrant the comparison.

Both NETs and RETs are path breaking innovations deployed to facilitate decarbonization and expectations are high in their ability to do so. However, as clean technologies, they face a double externality problem—knowledge spillovers and environmental degradation—that lead to the underinvestment in innovation and warrants subsidies [22]. In addition, avoiding emissions *via* RETs or removing emissions *via* NETs benefits the atmosphere, a public good, reasoning policy support to achieve the social optimum. Furthermore, in the urgency to reap the benefits and capture improvements from learning-by-doing, both technologies need to be deployed sufficiently early. However, this implies limited competitiveness when first deployed as well as high capital costs for demonstration projects and infrastructure requirements [18]. Moreover, the fear of environmental externalities, risks, and uncertainties hinder the diffusion of both NETs [23] and RETs [24], warranting regulatory measures.

Despite these similarities, notable differences exist that must not be overlooked. Firstly, NETs include multiple processes—capture, storage, transportation—potentially requiring different actors and thus, different instruments, while RETs consist of only energy production. Secondly, while RETs had the electricity market to integrate to, there is no discernible market to drive demand for NETs, at least not without considerable adjustments. Thirdly, while the role of RETs as a clean energy source was clear, the role of NETs is uncertain, whether a mitigation strategy, a bridging technology, or a last-resort technology. Finally, while the removal of emissions *via* NETs is a public good, RETs produce a private good. This affects the comparability of RETs and NETs.

Due to the commonalities in characteristics and obstacles, it can be argued that lessons learned from RETs are potentially valuable for NETs, yet the differences warrant care in transferring the results. Acknowledging both similarities and differences, the subsequent section uses the lessons from RET support and compares these to the proposals for NET policies.

Lessons from RET support for NETs

Research & development (R&D)

Acknowledging the nascency of NETs, the need for innovation to achieve cost reductions and efficiency gains is large. Due to the knowledge spillovers, private investments in R&D are commonly low [22] and hence, most countries support green innovations. However, NETs are rarely targeted specifically [10] and have to compete for financing with other more publicly accepted technologies like RETs [25]. Today, only the US awards production and investment tax credits [11], Canada provides investment tax credits [12], and Norway funds research grants[4] [13]. Therefore, proposals for NET policies include R&D support through grants or tax credits [26–29] and financial aid for demonstration projects [18, 30].

The importance of R&D support is highlighted by the experience with RETs. R&D policies effectively induced innovation [31–33], reduced costs [34] and improved efficiency [35] and hence, also supported the diffusion of RETs [36–38]. The experience with RETs also showed that the type of support matters: Subsidies outperformed tax credits for innovation [39] and deployment [38].

A targeted R&D strategy for NETs helps improve efficiency and reduces risks and uncertainties. We learn from RETs that this is best achieved using subsidies rather than employing tax credits. Although a tax credit scheme reduces government risk, R&D support aims to counteract the underinvestment of private investors that results from private risk [22]. Tax credits are better suited for mature NETs as they require a profitable firm to be applied and in case of a production tax credit, require a functioning technology. Since R&D subsidies are not contingent on either, they can support research for nascent NETs as well as incremental research, steering governments away from technological lock-in.

Fixed and premium payments

While R&D support can facilitate deployment, demand-pull instruments are better suited. Therefore, the introduction of premium payments, like Carbon Contracts for Difference are proposed for NETs. Thereby, the regulator acts as an intermediary, paying the difference between the (average) carbon price and the cost of removal for NETs [40, 41].

For RETs, feed-in tariffs play a similar role as fixed premiums to the electricity price. Feed-in tariffs effectively induced innovation [39, 42–44] and deployment [38, 45, 46], especially for nascent RETs, which required direct incentives to ensure competitiveness [47]. As important design elements, consistency [48], longer duration of contracts [49] and higher tariffs [50] increases the effectiveness of feed-in tariffs, yet these have also been criticized for reducing the cost-efficiency of the instrument [51].

Drawing on these findings, Carbon Contracts for Difference could ensure early deployment by making NETs competitive with comparable mitigation methods and hence, encourage innovation through learning-by-doing. However, to apply a premium payment requires a market for NETs. Voluntary carbon markets [52], niche markets [53], or linking NETs with an ETS could provide potential markets for NETs [54]. However, while Carbon Contracts for Difference make NETs competitive, demand for NETs would be market driven and volume and timing of NETs would not be regulated. This could encourage removal over mitigation, warranting separate targets for each [55].

Alternatively, the regulator could pay a fixed price for per tonne of carbon removed *via* NETs [56] as is currently employed in Denmark [14]. Such a public procurement strategy gives the regulator control over the type and the volume of NETs, expanding and contracting deployment as necessary [21]. Furthermore, in this case, removal *via* NETs is additional to abatement, hence, complementing decarbonization. Nevertheless, taxpayers have to bear the associated costs which, considering the negative perception of NETs [7], may facilitate opposition [21].

Mandates

Additionally, mandates are proposed to enforce the use of NETs in industries using carbon as input (like the oil or beverage industry) requiring the use of captured CO_2 or mandating a specific amount of emissions to be sequestered *via* NETs [17]. Alternatively, quota obligations may mandate the purchase of credits from NETs equalling their share GHG emissions [18].

The experience with RETs shows that mandates induce innovation [31, 39, 42]. However, despite obligating uptake, the effects on deployment were mixed and studies find both positive [57] and negative effects [58], the latter which can be partially explained by nonbinding targets [59] or lacking stringency [60]. Ultimately, mandates were more effective for mature technologies [38], yet were still outperformed by feed-in tariffs [61], which provide a safer investment environment than mandates [50].

For NETs, mandates would push cheap, mature strategies like BECCS over DACCS [6]. To avoid the possibility of lock-in, technology-specific mandates can encourage a portfolio of NETs [62]. Moreover, mandates can regulate the volume of NETs. For example, obligations could be initially low, increase until net-zero emissions are achieved and ultimately phased out to avoid dependence on NETs [21]. In addition, quotas can vary across sectors depending on their mitigation potential to ensure net-zero emissions in hard-to-abate sectors

[18]. Nevertheless, to be successful, mandates must be obligatory.

Auctions

Another demand-pull instrument proposed is auctions. Sweden currently plans a reverse auction scheme to award contracts to the lowest bidder, guaranteeing the purchase of negative emissions from BECCS [63]. In theory, an auction can implement NETs cost-effectively by revealing the true cost structure to the regulator [15]. Auctions were an important driver for investments in RETs [64], yet they did not support patenting activity [42, 64, 65], and results on the deployment of RETs under auctions were mixed [37]. Auctioned capacities were not necessarily installed due to financial hurdles [66] and limited competitiveness among bidders inflated costs [67].

Being a public procurement strategy, auction schemes allow the regulator to control the timing, volume and type of NETs considered. This is important to steer public acceptance, but as in the case of Sweden, the focus on a single technology may encourage premature lock-in and the expected high costs can lead to opposition.[5] In addition, the use of long-term contracts provides predictability to operators and incentivizes investments [18], although extensive contracts increase overall costs as seen with feed-in tariffs. As with RETs, NET operators may be unable to install pledged capacities due to high upfront costs [18] or betting on unrealized cost-reductions. Avoiding this pitfall requires sanctions [67] and financial help to build demonstration plants and infrastructure [18].

Carbon pricing

Currently, heavily discussed is the use of carbon pricing to induce NETs as many regions have carbon pricing schemes in place. It is assumed that a carbon price should indirectly induce NETs as removal becomes more expensive [68]. In addition, direct incentives are given in the EU ETS, whereby no allowances must be surrendered when using CCS [69]. Alternatively, it is proposed to integrate NETs into established ETS [70], allowing removal credits to be sold under the cap [20]. However, low and variable carbon prices contributed little to incentivize NETs [71] or to the innovation of RETs [42]. Nevertheless, carbon pricing induced the deployment of RETs [37, 72]. A market-based policy like carbon pricing relies on competitive, mature technologies [38] and thus, favoring low-cost RETs over expensive NETs.

On the one hand, without bridging the gap between the carbon price and cost of NETs, the integration in carbon markets alone will unlikely suffice to induce NETs as allowances remain cheaper [20], requiring additional financial support like carbon contracts for difference. On the other hand, if NETs are competitive, it may lead to mitigation deterrence [73]. Additionally, integrating NETs affects the stringency of the cap and thus, also the price [20]. The experience with offsets has shown that the price drop negatively affected the workings of ETS [74]. Therefore, integrating NETs requires amendments to the EU ETS [20] in addition to separate removal and mitigation targets to control both the volume of NETs and ensure mitigation [55].

Policy mixes

While most policies were proposed singularly, experts emphasize the necessity of a policy mix for NETs [75]. This is in line with the experience from RETs, showing positive interaction effects between R&D support and feed-in tariffs [31, 76] as well as mandates [77]. A well-balanced policy mix can improve the effectiveness of a policy—although at decreasing marginal effectiveness [78]. Knowledge is derived from both searching and doing and thus, a policy mix that includes both a technology-push and demand-pull instrument can foster both innovation and deployment of NETs. Only providing R&D support for NETs induces innovation but without clarifying the future role of NETs and ensuring demand, investments in NET-related R&D will be limited. Vice versa, providing a demand-pull instrument and market for NETs is insufficient if costs remain high, requiring R&D.

Discussion and conclusion

The previous section has shown that the theoretical merit of policies has in practice not always been achieved. Acknowledging the advantages and shortcomings of RET support can guide policy makers avoid past mistakes in creating an effective policy mix for NETs. However, the prior analysis largely relied on the similarities between RETs and NETs. Recognizing the differences in NETs and RETs—especially the different roles the two technologies can play in a country's decarbonization strategy—determines the effective policy mix for NETs.

NETs as an alternative mitigation strategy bring no additional environmental benefit compared to abatement as net-emissions are the same. Hence, market-based approaches under which NETs compete with other mitigation strategies are applicable. The integration of NETs into an ETS can instigate demand for NETs by legally allowing emitters to use NETs for mitigation. Integrating NETs into an ETS signals investment opportunities, encouraging innovation while deployment is driven by cost-effectiveness. However, the scale and timing of deployment of NETs is uncertain and will depend on the development of the carbon price. To ensure early competitiveness, a premium payment to cover the difference between the carbon price and costs could be deployed in addition to R&D support through grants and subsidies to amplify cost reductions. However, as removal is an alternative to mitigation, only net-zero emissions are attainable for sectors covered by an ETS and is, hence, unable to achieve either nation-wide net-zero emissions or net-negative emission in case of overshooting. In light of the risks and side-effects of NETs [6], the fear of mitigation deterrence [73], and the critical public perception [79], the public support for NETs as an alternative mitigation option is likely low.

Instead, NETs may act as a bridging technology to expediate decarbonization and enable later phasedown. Thereby, the use of NETs is restricted in volume, duration, and/or type. Accordingly, targets for NETs, mandates, or reverse auctions are suitable. Having targets for NETs when integrating them into an ETS allows regulators to control deployment and ensure continued mitigation. However, targets may not be met as NET uptake is driven by cost-efficiency and emissions can only be net-zero. Instead, binding mandates can control the volume and type of NETs, ensuring continued mitigation alongside the deployment of NETs. Direct costs would be carried by the emitter rather than the taxpayer, though increased abatement costs could lead to carbon leakage. Nevertheless, as NETs are controlled in volume and timing, profit opportunities for private actors are restricted, reducing investment incentives and requiring heavier state involvement. Therefore, public procurement strategies using reverse auctions are applicable. Auctions can ensure cost-efficiency and with long-term contracts can give investment security to operators. In addition, they guarantee that removal is additional to mitigation, making removal a public good and reasoning state involvement. To ensure installation, support for demonstration plants as well as general public R&D support can safeguard that NETs are deployable when needed and counteract reduced private R&D investments.

Finally, NETs may act as a last resort deployed at the 11th hour to achieve net-zero emissions when mitigation alone was insufficient for decarbonization. The late deployment of NETs warrants increased R&D support to offset limited learning-by-doing. Therefore, cost for removal would also be considerably higher. As the use of NETs is further restricted, public procurement may even be insufficient and NET operation may be state-led. All financing would be public, increasing the taxpayers burden although at the security that NETs are only deployed as a last resort.

Ultimately, the implementation of policy instruments to support NETs necessitates political willingness. Governmental support is a greater obstacle than technological feasibility for deployment [80] because "any lack of incentive … constitutes a disincentive" [81]. Furthermore, political willingness, measured by a coherent strategy for renewables, was a driver for their development [82]. In the context of NETs, political willingness has been absent, which is visible by the lack of incentives for NETs [83]. However, political willingness is fundamental considering the necessity of NETs to fight climate change yet perilous in light of the public perception.

This paper grounded its discussion of NETs on the deployment of RETs being the most extensively studied clean technology, providing the most comprehensive information to draw from. Nevertheless, the differences between NETs and RETs makes this a suboptimal though necessary comparison. Ethics drive the discussion surrounding NETs, more so than for RETs, thus what is optimal may not be what is deemed acceptable. Therefore, it is also important to study other (clean) technologies. In addition, as NETs lack the technological readiness for commercial deployment, the debate surrounding the deployment of NETs is hypothetical. Nevertheless, due to the risks associated with NETs, NET support requires long-term planning. As knowledge and experience with NETs grows, the role of NETs may shift and so too the policy instruments.

Notes

1. There is an ongoing discussion surrounding the semantics of CDR. Framing CDR as "natural" and "technological" elicits early judgment and should, thus, be avoided in policy correspondence (3,4).

However, as this article focuses on technological innovation and diffusion, I will refer to these terms, nonetheless.
2. Throughout this text, I refer to NETs to emphasize my focus on engineered solutions and their policy requirements.
3. Note, I disregard nuclear energy as a type of RET.
4. While there are currently no open calls for R&D, funding of past calls is ongoing till 2026.
5. The Swedish auction scheme is estimated to cost the government 180 mil€annually (16).

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