



Business Models for Negative Emissions From Waste-to-Energy Plants

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Negative emissions of carbon dioxide will likely be needed to meet the $<2^{\circ}\text{C}$ warming above the pre-industrial level goal of the Paris Agreement. A major technology option is combining Biomass Energy with Carbon Capture and Storage (BECCS) in the industry and power sectors. Biogenic waste contributes a major share for the numerous waste-to-energy plants around the world. This implies that adding a CCS facility to a waste-to-energy plant could establish a value chain for negative carbon dioxide emissions. Hence a waste-to-energy plant could deliver four services to society: waste management and avoided pollution, service district heating system, remove carbon dioxide from fossil-based waste categories, and generate negative carbon dioxide emissions from biogenic waste. A major barrier to deploying Bio-CCS at a waste-to-energy plant is a high investment and operation cost for the carbon dioxide capture plant, combined with lacking reward for the negative carbon dioxide emissions. In this paper I explore promising business models that could incentivize owners of waste-to-energy plants to install CCS facilities, assuming that government has established an infrastructure for transportation and permanent storage of carbon dioxide, as well as the basic framework for accounting for negative emissions. The business models are either founded on waste renovation customers being able and willing to pay for the additional cost of producing negative emissions of carbon dioxide directly or through certificates, or investments in CCS being incentivized by government through a guaranteed price or tax rebates for negative emissions of carbon dioxide.

Keywords: negative emissions, carbon capture and storage, waste-to-energy (WTE) plants, incentives for industry, business models

INTRODUCTION

To meet the climate policy goal of the Paris Agreement of $<2^{\circ}\text{C}$ warming above the pre-industrial level, large volumes of negative emissions of carbon dioxide will likely be needed due to slow and insufficient reductions of greenhouse gas (GHG) emissions (IPCC, 2018). Negative emissions or “Carbon Dioxide Removal—CDR” means removal of carbon dioxide from the atmosphere and permanent or at least long-term storage underground, in trees or other biomass, or in soil, minerals or the deep ocean. Combining bioenergy with Carbon Capture and Storage (CCS), so-called BECCS or Bio-CCS, is one of the technologies for negative emissions that has spurred most interest (Torvanger, 2019). Bio-CCS can be applied to power plants producing power and heat from biogenic materials, and waste-to-energy plants that have a sizeable share of biogenic feedstock. CCS

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applied to power plants and waste-to-energy plants are similar regarding carbon dioxide capture, transportation, and storage of carbon dioxide. The difference pertains to power plants designed to produce power (and possibly heat), whereas plants for incineration of waste are designed to handle waste removal, but that can also produce heat for district heating and some power. Waste-to-energy plants make sense as a first opportunity for developing Bio-CCS technologies since they produce four services, namely avoiding pollution through waste management, producing energy for district heating systems, avoiding carbon dioxide emissions from fossil-based inputs, and generating negative carbon dioxide emissions from biogenic inputs. Reduced emissions of the potent greenhouse gas methane from landfills could be added as a benefit of Bio-CCS. Therefore, CCS at waste-to-energy plants could constitute a relatively low barrier for deployment of Bio-CCS. At global level Kearns (2019) expects a strong growth of municipal solid waste generation due to population growth and rising living standards, with 70% increase from 2016 to 2050. The global average for waste of biogenic origin is at close to 70%, but the non-biogenic share has risen due to increased paper recycling and since more plastics have entered the waste streams.

A major barrier for CCS and Bio-CCS is high investment and operation costs compared to the value of avoided carbon dioxide emissions.¹ For Bio-CCS an additional barrier is a lacking system for accounting and rewarding negative emissions, more or less in all countries and regions (Schenuit et al., 2021). The backdrop for this regulation immaturity is found in the climate policy regime's presumption that use of biomass is climate neutral, given that regrowth of forest and other vegetation will capture and store the same volume of carbon dioxide. An additional explanation is the skepticism of some forest-rich countries with net loss of forest areas and biomass to have strict carbon dioxide accounting of deforestation.

Around 500 waste-to-energy plants are in operation in Europe (CEWEP, 2021). In 2019 the average for EU27 was 27% of waste materials used for energy production, 48% processed for recycling and composting, and 24% used for landfill. Thus, the potential of negative emissions from the waste sector in Europe is formidable.

The literature on technical, cost, climate, and life cycle aspects of negative emissions from Bio-CCS and waste-to-energy plants has grown the last few years but is still limited. Few studies exist of political and regulative barriers and how these can be overcome to generate incentives for industry to engage. A larger literature on business models for CCS as well as a broader set of negative emission technologies exists. Honegger et al. (2021) analyze CDR as a public good that should be provided and develop six functions that are jointly needed for this purpose: clarity on the role of CDR; accelerate R&D and learning; public engagement; transition to a cost-effective long-term policy framework; consistent monitoring, reporting and verification, and accounting; and identify and manage side-effects. Current policy mixes generally fail to address these functions, but Sweden

is best in class. The private market on CDR has developed faster than the public market, as indicated by the emergence of some market platforms for voluntary CDR services.² The funding of CDR needs will vary over time, in terms of up-front capital, funding for scaling up, and long-term funding that cover operation costs. Design of policy instruments and funding schemes should be differentiated according to a technology's maturity, cost, and permanence of carbon storage. Eventually, CDR should be included in broader policy instruments focused on efficient mitigation of greenhouse gas emissions. Cox and Edwards (2019) explore policies for negative emission technologies adapted to energy and transport, agriculture, sub-soil, and oceans. Recognizing insufficient policies and incentives for investments in negative emissions they argue that the non-climate co-benefits are valuable to produce a demand-pull for these technologies, for example energy provision related to BECCS. Payments for negative emissions could be sourced from carbon taxing, but with increased de-carbonization of society a steady increase of the tax rate to subsidize negative emissions would soon become politically infeasible. They note that societal transitions often result from national and regional political considerations, such as energy security, not foremost inspired by modeling studies e.g., recommending more carbon taxing. Roussanaly et al. (2020) examine the optimal design of CCS and value chains for waste-to-energy plants given several uncertainties related to costs and technical issues and provide associated cost estimates. Carbon dioxide can be permanently stored in saline aquifers or used for Enhanced Oil Recovery (EOR) (whereby the gas is injected into oil reservoirs to flush out more oil). Given the high cost of CCS they emphasize the importance of a financial credit for the negative emissions generated and a higher waste treatment fee due to the service of carbon dioxide removal. Fajardy et al. (2019) study technical, socio-economic, and regulatory bottlenecks for deployment of negative emission technologies, including bioenergy with CCS. Market and governance mechanisms are lacking, both locally and internationally. The existing literature is very limited so the significant regulatory and political barriers for efficient deployment of carbon dioxide removal require more research. They emphasize that carbon dioxide removal is a public good with a value that needs to be recognized and re-numerated through adapting carbon offsetting mechanisms, such as credits for negative emissions, and including negative emissions in emission trading systems. Platt et al. (2018) examine greenhouse gas removal technologies in the UK, finding that policies in the energy market and carbon credit mechanisms have the largest potential in the near term, since values in the markets for carbon dioxide use and storage are too low. A carbon storage credit mechanism should be developed. In a circular economy setting, Mikhelkis and Govindarajan (2020) assess the potential for incorporating CCS and combining the captured gas with slag from steel mills to produce building blocks at Stockholm Exergi's proposed waste-to-energy plant in Lövsta, noting that

¹By 7th May 2021 the allowance price for one ton of carbon dioxide in the European emissions trading system (EU ETS) was at about 51 Euro.

²Examples are Puro.earth, Nori, MoorFutures and max.moor, which offer CDR units based on biochar production, wooden or carbon-capturing building materials, agricultural carbon removals, or wetland and peatland restoration.

economic incentives are insufficient, e.g., in the form of subsidies and tax rebates for negative emissions of carbon dioxide. Fridahl et al. (2020) examine to what degree climate policy instruments at UN, EU or national level incentivize R&D and deployment of BECCS facilities in Sweden, finding that all the instruments are insufficient for generating demand and only partially cover R&D costs. For CDR to play a significant role in meeting Sweden's net-zero goal a substantial reform of its policy mix is called for, otherwise large direct support from government will be necessary. Sweden has proposed to introduce reverse auctions dedicated to BECCS. Such auctions are also named "procurement auctions," whereby suppliers of CDR facilities deliver a confidential bid to government for the price they charge for delivering a specified volume of negative emissions.

In this article I will examine how negative emissions from waste-to-energy plants can be facilitated through some promising business models that can provide sufficient incentives for industry to engage and have high feasibility in political and social terms. The research question of the study is:

What Are Realistic Business Models to Create a Value Chain for Negative Carbon Dioxide Emissions at Waste-to-Energy Plants?

I will assume that a regulative framework for CCS as well as an infrastructure for transportation and geological storage of carbon dioxide exists at national and international (European) level. The "Northern Lights" CCS infrastructure project, where construction work has started, is of relevance for Northern Europe.³

The next section discusses the necessary components of a value chain for negative emissions, before turning to four candidates for business models in section three. In section four the case of a business model for Bio-CCS at the Fortum Oslo Varme waste-to-energy plant based on increased waste fee is examined in some detail. In the fifth and final section the findings of this study are discussed.

A VALUE CHAIN FOR NEGATIVE CARBON DIOXIDE EMISSIONS FROM BIOENERGY

A working value chain for negative carbon dioxide emissions requires that the components of the chain perform satisfactorily and interacts in an efficient manner. The main components are production of biomass, harvesting, transportation, processing of biomass, combustion of biomass, capture of carbon dioxide, compression and transportation of carbon dioxide, and storage in geological formations.

Each step of the value chain must be sufficiently effective in terms of energy use, economic cost, and greenhouse gas emissions for a value chain to be viable in terms of resources

³A carbon dioxide transportation and storage infrastructure with the name of 'Northern Lights' is planned in Norway, initiated by Equinor, Shell and Total, with government support from Norway. The carbon dioxide will be transported by ships to a terminal at the Western coast in Norway, before being piped to a platform in the North Sea and injected into a geological formation 2600 meters below the seabed (Northern Lights, 2021). The expectation is to attract interest for using this infrastructure from large carbon dioxide emitters in other European countries. Currently some firms in various European countries as well as Microsoft have signaled an interest in linking to this CCS infrastructure.

and environmental impacts and to produce negative emissions of carbon dioxide (Torvanger, 2019). Given large-scale production of biomass for bioenergy, the risk of conflicts over land use implies that a broader interpretation of sustainability becomes vital. "Climate action" is only one out of UN's 17 sustainability goals (United Nations, 2021). Synergies between different sustainability goals should be sought, but nevertheless there can be trade-offs between climate action, loss of biodiversity ("Life on land") due to deforestation, availability of food ("Zero hunger"), and "Affordable and clean energy" (Smith et al., 2016). Increased biomass production may have ethical connotations both within countries and between countries, e.g., when developed countries import forest products from developing countries, which may affect local crop production. Buck (2016) reviews the literature on the social implications of rapidly increasing carbon dioxide removal activities, arguing that integrated empirical research on perceptions, barriers to adoption, drivers for new technologies, social impacts, and projections about negative emissions technologies can improve policymaking.

Accounting of negative emissions is not straightforward since removal of carbon dioxide from the atmosphere may have a different effect on atmospheric concentration and temperature than avoided emissions, e.g., from use of CCS (Jones et al., 2016; Zickfeld et al., 2021). This is due to the dynamics of the climate system linked to the global carbon cycle with carbon stored in oceans, the lithosphere, and the biosphere, with flows of carbon between these sinks. Since these flows works at different time scales, the relative effect of avoided emissions and removal of carbon dioxide will depend on the time horizon applied. As an illustration, removal of carbon dioxide from the atmosphere will reduce the absorption of carbon dioxide into the ocean sink. Furthermore, the value of negative emissions of carbon dioxide in the context of meeting a climate policy target is different from avoided ("positive") emissions. The value of negative emissions will increase in a situation where reducing emissions of GHG is not sufficient to meet the climate target, for example if we are in an "overshoot" situation where temperature and atmospheric carbon dioxide concentration have to be reduced, or in a case where the atmospheric concentration of carbon dioxide is reaching a tipping point where the rate of climate change and negative impacts accelerates. Removal of carbon dioxide would also become crucial if further reductions of emissions turn out to be overly difficult and costly. In terms of rewarding negative emissions these factors can lead to both lower and higher value for negative emissions compared to avoided emissions. These factors speak for separating the market for reduced emissions, foremost the EU ETS, and the market for negative emissions. In addition, it can be argued that combining positive and negative emissions in the "net-zero" goal concept EU and many countries are aiming at reduces transparency in climate policies and could lead to less emphasis on emission reductions (Rickels et al., 2020).

Turning to CCS and carbon capture applied to waste-to-energy plants, there are potentially two value chains in addition to the value of avoiding pollution from waste, heat production and reduced methane emissions from landfills. For fossil-based waste (e.g., plastics), a CCS value chain can be established. In addition, for the biogenic waste, a Bio-CCS value chain for negative

emissions of carbon dioxide can be established. Both value chains are using the same capture facility, as well as transportation and storage infrastructure. This difference lays in the different accounting and values of negative and positive emissions of carbon dioxide. This means that the value components of waste-to-energy are avoided pollution (from garbage and potentially air pollution), avoided methane emissions (which is a more potent climate gas than carbon dioxide) and energy production for district heating (and potentially saved fossil fuel use). With investments in carbon dioxide capture, the value of reduced carbon dioxide from fossil-based waste and the value of negative emissions from biogenic waste can be added. This means that the net cost of establishing carbon dioxide capture at a waste-to-energy cost can be subtracted the value of pollution avoidance from waste, energy production, and avoided methane emissions. Since carbon dioxide capture is energy-demanding (“energy penalty”) the heat and power output of waste-to-energy plants will be severely affected. Bisinella et al. (2021) analyze the effects on energy and greenhouse gas emissions of adding carbon capture to municipal solid waste incineration plants, finding that carbon capture facilities reduce electricity output by one-third and halves the energy output for combined heat and power plants. The efficiency of carbon capture is the most important factor explaining the overall efficiency of reducing carbon dioxide emissions (including the effect of the energy produced replacing fossil fuels).

For the broader CCS value chain, the additional costs of the required infrastructure for compression, transportation and storage of carbon dioxide must be added, but the infrastructure cost can be shared among all point sources of carbon dioxide connected to the CCS infrastructure. An infrastructure for transportation of carbon dioxide by pipelines (or by ships) and storage of the condensed gas deep in geological formations involves large investments with “economies of scale” properties and coordination issues.⁴ Therefore collaboration between many emission sources of carbon dioxide and across countries will reduce costs and facilitate investments in an infrastructure. Moreover, government involvement can share risk and reduce coordination problems across the value chain. Carbon dioxide capture, transportation services and storage services can involve different companies, where the return on an investment depends on other investments along the value chain. In addition, open access to pipelines and storage is important to avoid that a dominating company can charge monopoly prices and reduce overall societal value of the CCS infrastructure. For these reasons and since CCS could be considered as a basic infrastructure for society—like a power grid, public-private partnership should be a favored funding scheme for a CCS infrastructure. “Northern Lights” is an example of government facilitation of a CCS infrastructure in Norway and the North Sea in collaboration with oil companies (Northern Lights, 2021).

⁴Economies of scale properties mean that that the cost of transportation and storage per ton of carbon dioxide will fall with the volume of the gas handled, for one reason because the capacity of a pipeline increases more with the diameter than the cost.

The national and international policy-economic conditions (e.g., the Paris Agreement and EU climate policies) affecting carbon dioxide emissions, energy and waste management will significantly affect costs and value of Bio-CCS and thus its viability applied to waste-to-energy plants. Examples of such conditions are value of avoided carbon dioxide emissions (e.g., allowance price in the EU ETS or carbon taxes), government regulative and money support for CCS, and the possibility of specific rules for accounting and rewarding negative emissions. In a study of nine OECD cases Schenuit et al. (2021) find that some CDR policies are in place, and more are emerging due to the uptake of net-zero emission goals by 2050 in many countries. Such policies include accounting of CDR in mitigation targets, methods to address ecosystem- and geochemical-related issues, relation to the broader climate policy-mix, and government support. The UK is the most proactive country on CDR policy entrepreneurship, followed by Sweden, the EU and Norway. Australia and New Zealand aim at early integration and fungibility of CDR policies with other climate instruments. Many countries have less developed CDR policies, which can be characterized as an incremental modification of existing climate policies. The European Commission is preparing a regulatory framework to certify robust and transparent carbon removals, starting with bio-related removals, with an aim to complete this by 2023 (van Renssen, 2021).

Even if economic support from government may be necessary to enable Bio-CCS at an early stage, a sizeable support will not be sustainable. Therefore, business models to attract business involvement in Bio-CCS that are independent of specific monetary support from government will be required. In the next section four business models for Bio-CCS at waste-to-energy plants are explored, with different levels of government involvement.

BUSINESS MODELS FOR BIO-CCS AT WASTE-TO-ENERGY PLANTS

The world’s first marketplace for carbon dioxide removal certificates became operational in January 2021, aimed at companies voluntarily funding carbon dioxide removal projects. The company Puro offers three types of carbon removal certificates: from carbonated building materials, wood used for buildings, and biochar (adding charcoal to soil) (Shrestha, 2019; van Renssen, 2021).⁵

The candidates for business models for enabling and incentivizing Bio-CCS at waste-to-energy plants discussed in the following are: Increased renovation fee; Certificates for negative emissions; Guaranteed price by government; and Government tax credit. Combinations of these alternatives are possible.

⁵Puro is set up by the Finnish companies Fortum, Tieto, Valio, St1, ÅF Pöyry, Compensate Foundation, Carbofex, Yara Suomi Oy, Lassila & Tikanoja, SOK, Orbix, Nordic Offset, and Hedman Partners, in collaboration with the global financial solution company South Pole and the Swedish bank SEB.

Increased Waste Fee

Households and firms are paying for renovation services organized at the municipal or city level. Investing in Bio-CCS and operation of carbon dioxide capture involve substantial costs. The question then becomes if it would be feasible to cover this additional cost through an increased renovation fee for households and firms. In the next section I present an illustrative case for the planned carbon capture plant at the Fortum Oslo Varme waste-to-energy plant in Norway. With the assumption of covering the additional net present cost of investment and operation over a 25-year period, I find that the annual fee per ton of waste would have to increase by around 85% to fully cover the additional cost of carbon capture at the plant. The question is whether an increase of the waste fee of 85% may be feasible in the city of Oslo, since the additional cost will reduce the competitiveness of firms based in Oslo and be challenging for low-income households. Low-income households could get some compensation from reduction of other municipal taxes that depend on income or value of property. On the other hand, increasing the renovation fee by around NOK 8000 annually for an average household may be considered as moderate, e.g., compared to the property tax in Oslo.⁶ Conditional on Fortum Oslo Varme raising half of the funding the Norwegian parliament has decided on government funding of the remaining half of the CCS cost. Should this work out only a minimal increase of the waste fee would likely be needed for complete funding of the CCS facility at the Fortum Oslo Varme plant.⁷

Certificates for Negative Emissions

Negative emissions could be stimulated through a system of negative emission certificates, whereby each ton of demonstrated capture and storage of carbon dioxide from biogenic sources at a waste-to-energy plant is allocated a certificate. These certificates will have a value. In their techno-economic and environmental impact assessment of municipal solid waste incineration systems with and without CCS, Pour et al. (2018) discuss a negative carbon dioxide refunding scheme, where operators of BECCS plants receive a refund for each ton of carbon dioxide they remove from the atmosphere. Such a certificate system has similarities to GHG credits, for example the Clean Development Mechanism (CDM) under the Kyoto Protocol (Torvanger et al., 2013). This implies that a standardized Monitoring, Reporting and Verification (MRV) system for the CDR certificates is called for, to ascertain that the negative emissions are credible. Such certificates can supplement carbon taxes and emissions trading systems and broaden the climate policy mix and increase overall efficiency without requiring a “hard-linking” that is problematic with the current design of e.g., the EU ETS (Rickels et al., 2021).

⁶The tax rate is 3 ‰ of the property value. To make the property tax in Oslo more socially acceptable the tax is only applied to property value above 4 million NOK. An additional annual waste fee of 8000 NOK is equivalent to 924 USD, given a currency exchange rate of 8.659 (2 July 2021).

⁷Fortum Oslo Varme has applied EU's Innovation fund for funding of about half of the CCS cost. This fund supports demonstration of innovative low-carbon technologies. If this application is successful and adding the funding from the Norwegian Government, the complete cost of carbon dioxide capture at the Fortum Oslo Varme plant would more or less be covered by public money.

Government can determine the value of the negative emission certificates or producers of negative emissions can set a value that buyers of certificates are willing to pay. Buyers can be producers of biogenic materials such as sawmills and timber producers, government, private persons, firms, or organizations that are willing to finance production of negative emissions. Buyers can be motivated by developing a more climate-friendly profile, or by some type of government regulation requiring production of negative emissions by companies using biogenic resources or to compensate for fossil-based carbon dioxide emissions. If the need for negative emissions increases in some years, government can take steps to increase the price of negative emission certificates to induce more production.

Government Guaranteed Price

The government can guarantee a price on production of negative emissions, to be paid to waste-to-energy plants (and other entities) that can document production of negative emissions through use of biogenic resources combined with carbon capture and storage. In this case the market for negative emissions is entirely established by political decisions, but this is also the case for carbon taxing and carbon dioxide emissions trading systems. In this case the government or its agency is the market maker, acting like a “bank” for negative emissions, where the producers are reimbursed with the help of public money, implying a need to reduce budgets for other societal needs or increased taxing. Like negative emission certificates a guaranteed price can work as a supplement to taxing and emission trading, broadening the climate policy mix and increasing overall efficiency. In such a system it is straightforward for government to increase incentives for production of negative emissions through increasing the guaranteed price on negative emissions.

Government Tax Credit

The workings of a government tax credit for production of negative emissions is similar to a guaranteed price but would only be of interest to waste-to-energy plants or other industry plants using biogenic resources that could invest in carbon dioxide capture to establish a negative emissions value chain, and which are exposed to some type of taxing by government. Like a guaranteed price, tax credits can be adjusted to strengthen incentives for production of negative emissions.

A CASE STUDY: FORTUM OSLO VARME'S WASTE-TO-ENERGY PLANT

Midttun et al. (2019) discuss the potential for financing and pricing carbon dioxide capture at waste-to-energy plants in cities, finding that there is a considerable potential for carbon capture in Northern Europe. In the context of the planned Northern Lights CCS infrastructure project and the Fortum Oslo Varme case, they expect that a further increase of the carbon price in EU ETS will enable full private financing of the next generation of carbon capture plants. Fortum Oslo Varme's waste-to-energy plant in Norway is an interesting case

since this plant has been one of three candidates for a full-scale carbon capture facility in Norway (Stuen, 2017).⁸ A pilot capture facility at the plant was in operation in 2019. In autumn 2020 the Norwegian parliament decided to provide full government funding of Norcem Heidelberg's cement production plant in Brevik, Norway. In addition, a carbon capture plant at Fortum Oslo Varme's plant will receive about half government funding, conditional on remaining funding from other sources. An application for additional funding is submitted to EU's Innovation Fund (Simon, 2021). The government's CCS initiative encompassing Norcem Heidelberg and Fortum Oslo Varme is named "Langskip" (after a common ship type from the Viking era). Feasibility studies have been done for these industrial CCS candidates. For the Fortum Oslo Varme waste-to-energy plant the capital cost has been estimated at about 4.5 billion NOK and the annual operation cost at 230 million NOK (Gassnova, 2020). Since close to 50% of the income of the plant is from the heat and electricity markets an energy-demanding carbon capture facility will introduce an additional cost element (Midttun et al., 2019). In the following calculations, however, I assume that all important components are included in the cost estimates from Gassnova. The biogenic share of waste at the plant is estimated at 50–60%. The waste-to-energy plant Fortum Oslo Varme plant is not included in EU ETS but is paying a Norwegian carbon dioxide tax on fossil-based emissions from January 2021.

Based on these cost estimates a simple calculation of the additional cost from installing a full-scale carbon capture facility at Fortum Oslo Varme's waste-to-energy plant can be made. The additional benefits of carbon dioxide capture at the plant are negative emissions for half of the emissions, namely 200,000 tons of carbon dioxide annually, and avoided emissions for the residual fossil-based 200,000 tons. These benefits are additional to the benefits of waste management and energy production for district heating in Oslo (and in principle avoided methane emissions from landfills). The calculation is based on the net present cost and value given a 25-year time horizon. The results for the full additional costs are presented in **Table 1**. A detailed explanation of the calculation method is found in **Appendix 1**. These cost estimates depend on several assumption and should only be interpreted as indicative and relative to the current waste fee in Oslo. The additional cost to cover the net present cost of a full-scale carbon dioxide capture plant is estimated at NOK 2,716 per ton of waste, implying an around 85% increase of the waste fee.⁹ The cost in the numerical example presented in **Table 1** should be interpreted as the social (societal) cost of installing carbon dioxide capture (but excluding the relevant share of the investment and operation costs of the national transportation and storage infrastructure for carbon dioxide, confer the Northern Lights project).

⁸The other candidates have been the Norcem Heidelberg cement production plant in Brevik and Yara Norge's fertilizer production plant in Porsgrunn. Yara later withdrew from the CCS plans.

⁹Given a currency exchange rate of 8.659 (2 July 2021) this is equivalent to 314 USD.

TABLE 1 | Cost of full-scale carbon dioxide capture at the Fortum Oslo Varme waste-to-energy plant.

Case for calculating waste fee	Waste fee, NOK per ton of waste	Annual waste fee for an average household or business, NOK
Current fee for mixed household and business waste ^a	3187	9561
Additional waste fee to cover cost of carbon dioxide capture facility	2716	8148
Waste fee included full cost of carbon dioxide capture facility	5903	17709

^aThe waste fee is calculated as the average annual waste fee for a 400 liter container in Oslo for households (NOK 10463) and business (NOK 9426). Based on net present value calculations with 25-year time horizon and 3% discount rate.

As shown in the table the average household and business in Oslo would have to pay about NOK 8000 more in waste fee annually to cover the full cost of carbon dioxide capture at Fortum Oslo Varme waste-to-energy plant.

DISCUSSION

A value chain for negative emissions of carbon dioxide at waste-to-energy plants requires working policy & regulation, technical, and economic frameworks, which implies that these frameworks are efficient as well as feasible in political and social terms. To significantly strengthen production of negative emissions significant progress is needed in terms of policies and regulations, availability of infrastructure for transport and storage of carbon dioxide, and business models providing incentives for industry.

A framework for policies and regulation of negative emissions is currently missing, in part due to the general assumption in the climate policy regime that biomass is neutral in terms of carbon dioxide, and in part due to negative emissions getting more attention after the release of IPCC's 1.5°C special report (IPCC, 2018). In addition, many countries are aiming at net-zero GHG emissions by 2050, which requires substantial amounts of negative emissions. Regulation and accounting of negative emissions, including linking to climate policies and instruments, however, are being developed under the Paris Agreement rulebook and at regional and national level, e.g., in the EU (Honegger and Reiner, 2018; ClydeandCo, 2021).¹⁰ Negative emissions cannot be included in the current version of EU ETS since biomass is considered climate neutral and companies involved in biomass production are not included (Torvanger, 2019). Rickels et al. (2020, 2021) explore different options for integrating negative emission technologies into the EU ETS, where one option is contracts ("contracts for difference") that guarantee a fixed price per ton of carbon dioxide removed

¹⁰Since the Paris Agreement puts much more emphasis on carbon dioxide sinks and land use and changes than the predecessor (the Kyoto Protocol) did, more elaborate rules and regulation of negative emissions are deemed necessary.

by paying the difference compared to the EU ETS allowance price. Another option is for a regulatory authority to act as an intermediary buying carbon dioxide credits and selling them on the EU ETS market, dependent on the allowance price, as a type of market stability tool. However, the authors note that integration of NETs into the EU ETS would require a fundamental amendment to the EU ETS Directive. The EU is emphasizing so-called nature-based options to remove carbon dioxide from the atmosphere, meaning increased forest biomass and more land-use related fixation of carbon dioxide (for example in soil) (European Parliament, 2021). Since negative emissions of carbon dioxide differ from avoided emissions in terms of role in the global carbon cycle and reaching a climate policy goal, the regulation system should also differ. The importance of the difference between positive and negative emissions will likely increase over time in line with increased global warming and difficulties of reducing emissions from e.g., agriculture.

Developing a value chain for negative carbon dioxide emissions requires availability of an infrastructure for transportation of carbon dioxide by pipeline or ships and geological formations prepared for injection and storage of compressed carbon dioxide. Currently only a few and local components for such an infrastructure exist, but initiatives to build larger infrastructure systems have been taken, for example in the U.K. and Norway (Northern Lights, 2021).

The third framework required consists of business models, whereby industry can see negative emissions as a business opportunity, even if some direct government support may be necessary in the first phase. This demands that a sufficient value is attached to negative emissions to cover the capital and operation costs and compensate for the inherent risk of investing in new technologies, being dependent on political decisions. Since negative emissions differ from positive emissions with respect

to meeting climate targets, accounting and regulation should also differ.

This article has discussed some candidates for business models for waste-to-energy plants: increased waste fee, certificates for negative emissions, guaranteed price by government, and a tax credit. Countries will likely choose different models and designs dependent on national conditions. The case study of the Fortum Oslo Varme plant in Norway indicates that at least a part of the cost of a carbon dioxide capture facility at waste-to-energy plants could be financed through an increase in the waste fee paid by households and businesses.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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APPENDIX 1

Calculations for the Fortum Oslo Varme Case Study

This appendix describes a straightforward and simplified method to estimate the necessary increase of the waste fee if households and firms in Oslo were to cover the full investment and operation cost of a carbon dioxide capture facility at the Fortum Oslo Varme waste-to-energy plant in Oslo. The Fortum Oslo Varme waste-to-energy plant is the largest in Norway, with an annual capacity to incinerate 375,000 tons of waste, based on Norwegian and international residual waste, annually producing 150 GWh power and 700 GWh for district heating in Oslo (2017) (Fortum Oslo Varme, 2021a; Stuen, 2017). The plant is generating 400,000 tons of carbon dioxide, of which about half is from biogenic waste (Fortum Oslo Varme, 2021a,b). Thus 200,000 tons of carbon dioxide is bio-related and the remaining half fossil-related.

According to Gassnova (2020) the capital cost of a carbon dioxide capture facility is estimated at 4.5 bill. NOK and the annual operational cost at 230 mill. NOK. It is assumed that all important cost elements are included in these figures. The cost of infrastructure to transport and store the carbon dioxide under the North Sea seabed is not included (confer the discussion of the Northern Lights CCS infrastructure project). The calculation is based on the net present investment and operation cost of the carbon dioxide capture facility over a 25-year period.

In January 2021 Norway introduced a tax on fossil-based carbon dioxide emissions from waste incineration. The tax rate is at 149 NOK per ton of carbon dioxide, which translates to 82 NOK per ton of waste given the 50 % fossil-based share of waste (Fortum Oslo Varme, 2021c). In absence of a carbon capture

facility the carbon tax would be transferred to households and firms through an increased waste fee. If Fortum Oslo Varme invests in a carbon capture facility, the saved carbon dioxide tax can be subtracted from the waste fee, implying that the waste fee can be brought back to the previous level (without the tax-related increase). Therefore, the carbon tax is disregarded in the calculations.

A sensitivity analysis is done for discount rates between 2 and 5 %, but this shows only a minor effect on the additional waste fee required for financing carbon capture, so a 3 % discount rate was chosen. Extending the project period from 25 to 35 years reduces the required waste fee increase since the initial investment cost can be shared over more years of waste fee payments.

The reference waste fee is calculated to compare with the increase required to cover the cost of carbon dioxide capture. This is based on the average annual waste fee in Oslo for households (NOK 10463) and business (NOK 9426) for a 400-liter container that is emptied once a week, and assuming that 1000 liters mixed household and business waste weighs 150 kg (Oslo kommune, 2021; Norsk Gjenvinning, 2021). A 400-liter container is taken as an average across companies and private households, in the absence of more detailed data. Given full waste containers every week this implies that the average household and business in Oslo produces about 3 tons of waste annually.

The calculations summarized in **Table 1** show that the average annual waste fee would need to increase by about 8000 NOK to cover the cost of carbon dioxide capture, which means an increase of about 85 %. If the project period is extended to 35 years the required waste fee increase would be lowered to around 7000 NOK.