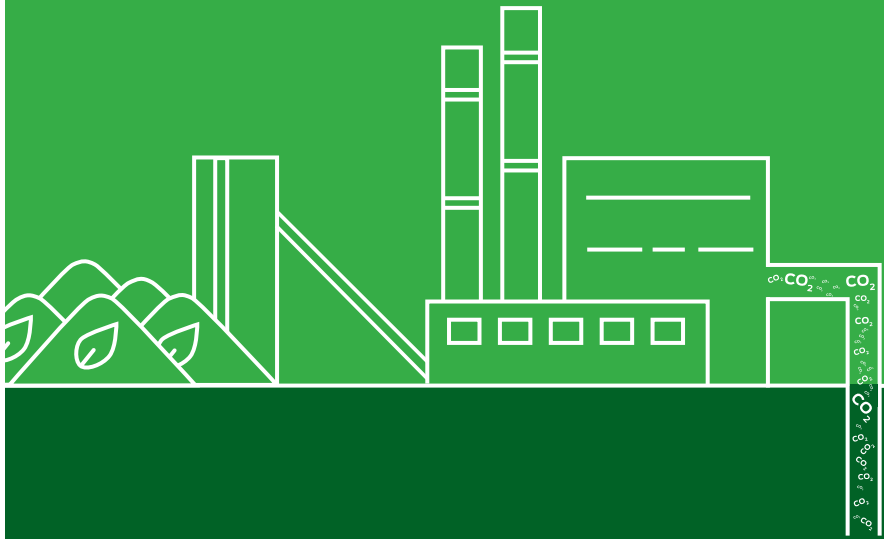


Edited by Mathias Fridahl

# Bioenergy with carbon capture and storage

From global potentials to domestic realities



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**FORES**



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# Author biographies

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# Foreword

Oliver Geden

**When I first encountered** “negative emissions,” I thought it to be nothing more than a dubious category in climate-economic modeling, a way to balance remaining global carbon budgets despite continuously rising emissions, a way to avoid declaring that limiting warming to 2°C is no longer feasible. In fact, until the Paris Agreement, negative emissions worked just like that, all the more since climate policymakers around the world avoided dealing with the need for large volumes of carbon dioxide removal.

Over time I learned that there is much more to it. If afforestation/reforestation and ecosystem restoration are already seen as credible approaches to removing carbon dioxide from the atmosphere, why not create more sinks like that? If we already use biomass in the energy sector and in principle know how carbon capture and storage works, why not try to combine them? And if engineers believe that direct air capture and storage or enhanced mineral weathering could one day become efficient approaches, why not at least put more effort into research and development?

Since the adoption and early ratification of the Paris Agreement, more and more policymakers have started to deal with the need for and the prospects of negative emissions, not only because the new (though aspirational) temperature target of 1.5°C requires even larger volumes of negative emissions, but probably even more because of the newly introduced target of *net-zero emissions*. While primarily seen as an intermediate step in reaching the new, ambitious temperature target, negative emissions also open the way for a more pragmatic perspective on carbon dioxide removal. Since it is impossible or too expensive to completely eliminate all emission sources (e.g., from agriculture or aviation),

carbon dioxide removal will be needed simply to offset these *residual emissions*.

Sweden has already decided on a net-zero emissions target (by 2045), with the UK likely to follow. Expectations are high that the European Commission will make net-zero emissions an integral part of its new long-term climate strategy, a move the European Parliament successfully induced by introducing net zero in the negotiations on the EU's Energy Union Governance Regulation. Framing carbon dioxide removal as an integral part of a net-zero strategy has three main advantages: First, the necessary volumes would be quite limited. Second, conventional mitigation will still be seen as the priority. Third, every key emitter (i.e., the European Union, its Member States, as well as cities and companies) will need to find individual ways to bring their emissions to net zero and will have to consider very different negative-emission approaches, probably choosing those that work best for them and their constituencies. Taken together, this will probably lead to a situation in which negative emissions are not primarily seen as *geoengineering* (i.e., a deliberate large-scale intervention in the climate system), but just as an unconventional form of mitigation.

This book is the first to bring together a broad range of policy-relevant perspectives on negative emissions and, in particular, on bioenergy with carbon capture and storage: global modeling, climate diplomats' views, European and national climate policymaking, and early attempts at using carbon dioxide removal approaches in urban district heating systems. The book's value lies not only in the range of issues covered, but even more so in discussing the practical challenges and potential opportunities for policymakers and businesses. I am sure this book will make a major contribution to the emerging debate on how Europe can deliver its fair share in the context of the Paris Agreement.

**Oliver Geden**

23/09/2018, Berlin, German Institute for International and Security Affairs



# Executive Summary

**This book explores** the role of bioenergy with carbon capture and storage (BECCS) in climate governance. It starts by discussing BECCS' global mitigation potential, as depicted in the idealized world of climate scenarios. Chapter 2 shows that almost all climate scenarios compatible with the high likelihood of limiting global warming to 2°C deploy BECCS. While excluding BECCS from these models' technology portfolios does not necessarily make 2°C compatible scenarios impossible, it does mean that the projected cost of meeting that goal increases.

In this context, based on interviews with integrated assessment modelers, chapter 3 illustrates how the use of the word “projected” is deliberate and significant. The modelers insist that they are dealing with projections, not predictions. At the same time, this modesty is contrasted to a core willingness to wield political influence.

Chapter 4, which applies a crude method to map European point sources of biogenic CO<sub>2</sub>, indicates that the scenarios for Europe can be associated with factual potentials. The European pulp and paper industry emitted approximately 60–66 Mt of biogenic CO<sub>2</sub> in 2015. To a lesser extent, there is also potential to capture biogenic CO<sub>2</sub> from the production of electricity, heat, and biofuels.

While R&D into BECCS has previously been framed as a “slippery slope” triggering objectionable consequences, for example, concerning food security, chapter 5 argues that realizing BECCS should instead be seen as an uphill struggle. This conclusion gains support in chapter 6, which maps existing policy incentives for BECCS. This exercise reveals an almost complete lack of political initiatives to deploy BECCS, indicating that the climate scenarios' large-scale

deployment of BECCS could be seen as detached from reality.

The book ends with chapter 7, which illustrates how UN and Swedish climate policy objectives have indeed influenced companies to get involved in planning for negative emissions, but also shows how the lack of policy incentives has put “sticks in the wheel” when it comes to affirmative investment decisions. While some funding sources for R&D and capital expenditures are highlighted, the primary concern is the lack of market pull that would provide revenues to cover operational expenditures.

This book highlights the many caveats involved in moving from the theoretical potentials identified at the global scale to economically viable potentials facing investors at the business scale. It concludes that overcoming the challenges associated with realizing the theoretical potentials will be daunting, a true uphill struggle. Yet, with appropriate policy incentives, BECCS may still come to play an important role in the struggle to limit global warming to well below 2°C.

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## Chapter 1

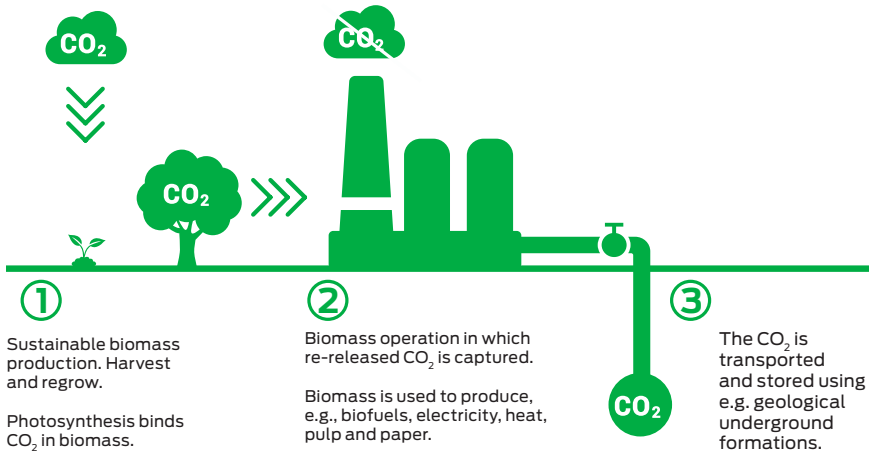
# Introduction

Mathias Fridahl

**The effects of climate change** are becoming more and more evident. Global temperatures have increased more than 1°C since preindustrial times. Sea levels are rising. Weather patterns are changing. Despite obvious signs of climate change, global greenhouse gas (GHG) emissions continue to increase. Projections look gloomy too: when evaluating the collective ambition of countries' Nationally Determined Contributions to the Paris Agreement, current emissions are expected to rise by almost 30% by 2030 (UNEP, 2017). With current levels of global emissions, the carbon budget for meeting the goal will be depleted in about 8–22 years from 2017 (see chapter 2). This makes the transformational change required to hold global warming well below 2°C at the end of the century, the stipulated goal of the Paris Agreement, appear distant.

In this context, bioenergy with carbon capture and storage (BECCS) has emerged as a key mitigation technology (Figure 1-1). Various proposed BECCS technology systems exist, all of which exploit the ability of plants to absorb carbon dioxide (CO<sub>2</sub>) from the atmosphere when growing (through photosynthesis). The biomass is then used in various operations in which the re-released CO<sub>2</sub> is captured, transported, and stored geologically. Although the origin of the CO<sub>2</sub>, whether fossil or biogenic, makes no difference for the atmosphere's ability to trap heat, the theoretical potential of BECCS to achieve global “net negative” emissions would make it possible to buy time for the climate transition while still achieving balance at budget closure in 2100. BECCS arguably allows the repayment of what seems to be an inevitable carbon budget deficit generated in the near term through massive removals of CO<sub>2</sub> from the atmosphere in the long term.

Figure 1-1 | Principle of bioenergy with carbon capture and storage (BECCS).



This book explores the role of BECCS in reaching climate policy objectives. It is motivated by a conundrum: on one hand, a growing climate modeling literature says that meeting the Paris Agreement’s global temperature goal is unlikely without deployment of BECCS; on the other hand, a growing scientific literature questions the feasibility of deploying BECCS at the scales suggested in the climate scenarios. While modelers acknowledge their crude approximation or complete exclusion of the various techno-economic limitations, the bearing capacity of natural resources, and political and social dimensions of BECCS in their scenarios, several researchers now struggle to define mitigation alternatives that could enable achievement of the temperature goal without vast deployment of BECCS, which they consider likely to be politically and socially infeasible.

To investigate this conundrum, the book moves from exploring global theoretical potentials to the practical challenges facing companies planning for site-specific deployment. To take on this task, the story starts by exploring global climate scenarios and ends in a concrete case of planning for BECCS deployment in Stockholm’s district heating system. All along, Sweden will be a “red thread” throughout the book. Centering the narrative on Sweden is

justified by the country's unusually good preconditions for BECCS, such as an already well-established bioeconomy with large point sources of biogenic CO<sub>2</sub> combined with ambitious climate policy objectives and high capacity to finance and implement new technologies.

The book starts by outlining the global potential for BECCS as depicted in the idealized worlds of climate scenarios. It moves from exploring the magnitude of BECCS deployment in climate scenarios and outlines the caveats raised in the modelling literature.

In **chapter 2** (“BECCS in Climate Scenarios”) discusses the carbon budgets for the 1.5°C and 2.0°C targets and their relationship to BECCS. The chapter also gives an overview of the role of BECCS in the IPCC's Fifth Assessment Report (AR5) and in Shared Socioeconomic Pathway (SSP) scenarios provided by integrated assessment models (IAMs). It will also discuss the main assumptions regarding BECCS made in such models.

**Chapter 3** (“Views of BECCS Among Modelers and Policymakers”) moves from exploring the magnitude of BECCS deployment in climate scenarios to outlining caveats raised by modelers themselves. The chapter addresses how modelers navigate the landscape of political and academic pressures to deliver timely, insightful, and relevant policy advice despite inherent and crucial uncertainties and increasing model complexity. Based on interviews with modelers, the chapter discusses perspectives on uncertainty, the communication of IAM results, and the models' relationship to reality. The chapter also discusses views of BECCS among policymakers whom generally want to give relatively low priority to investments in BECCS. Failing to invest in the future delivery of BECCS, combined with today's lack of mitigation ambition, limits future generations' maneuvering room to resolve the climate crisis.

**Chapter 4** (“European and Swedish Point Sources of Biogenic Carbon Dioxide”) explores crude methodologies for mapping European point sources of biogenic CO<sub>2</sub>. That the potential for BECCS in Nordic pulp and paper produc-

tion is high is well established. However, through combining data from different emission registries, previously hidden potentials for BECCS in Portugal can be revealed. For other sectors with BECCS potential, such as combined heat and power (CHP) and bioethanol, accounting practices and data shortages make it harder to map point sources. A crude estimate is provided at the European level, the used being exemplified by a more finely grained mapping at the Swedish level. The results indicate that substantial point sources of biogenic CO<sub>2</sub> exist in these sectors too, though with high uncertainty.

**Chapter 5** (“Governing BECCS: “Slippery Slope” or “Uphill Struggle?””) highlights how BECCS and other large-scale interventions in the Earth’s climate system, proposed to moderate anthropogenic global warming, are commonly portrayed as threatening to initiate a “slippery slope” from research to deployment. The argument suggests that governance should constrain or even proscribe research into BECCS on the grounds that allowing it to proceed unchecked could lead to a chain of events resulting in deployment and the undesirable consequences that this might bring. This chapter begins by critically examining the slippery slope argument as articulated in relation to BECCS. It then draws on the empirical findings of an expert scenario method designed to explore how far BECCS might develop in the future and under what governance arrangements. Rather than a slippery slope, the scenarios instead illustrate what might best be described as an “uphill struggle,” in which BECCS innovators confront manifold technical, political, and societal challenges to deployment. The chapter concludes by seeking to reframe the governance task as one of responsible incentivization, rather than one of constraint or proscription.

**Chapter 6** (“Multilevel Policy Incentives for BECCS in Sweden”) builds on the high potential for BECCS in Sweden identified in chapter 4, summarizing the current policy incentives for BECCS research, development, demonstration, and diffusion (RDD&D). It examines the given policy drivers and obstacles at multiple scales (e.g., international, supranational, and national) and in terms of various forms of instruments (e.g., economic, regulatory, and informational).

The chapter concludes that current policy instruments mostly fail to incentivize BECCS RDD&D in Sweden. The instruments partly favor R&D yet fail to provide incentives covering operational costs. Under current circumstances, BECCS is unlikely to reach demonstration scale in Sweden.

**Chapter 7** (“Spearheading Negative Emissions in Stockholm’s Multi-energy System”) discusses the prospects for BECCS in Stockholm. In Stockholm, CO<sub>2</sub> emissions from the production of district heating and electricity have been reduced by 75% relative to 1980 levels, and soon production will be almost climate neutral. Is it then time to lean back and relax, to wait for others to catch up and do their jobs? With the achievability of the Paris Agreement’s temperature goal called into question, it can be argued that no one can afford to stand still. In a system completely decarbonized from fossil CO<sub>2</sub>, setting one’s sights still higher would mean achieving negative emissions. The Stockholm energy system could be a forerunner, lighting the path for others. To attain negative emissions, plenty of conditions and circumstances need to be in place—not least, policy instruments. In this chapter, an example pathway from emitter to “demitter” will be outlined, as well as the policies required to enable that transformation.

**Chapter 8** (“Conclusions”) summarizes the practical limitations to the global modelled potentials for BECCS, not least the caveats introduced by modellers themselves, lack of political prioritization, juridical contradictions between different scales of governance, and the policy disincentives making BECCS economically unviable. Overcoming these challenges is a daunting task, a true uphill struggle, yet it is not unimaginable. With appropriate policy incentives in place, developed responsibly through an inclusive policy process, BECCS may still come to play an important role in the struggle to limit global warming well below 2°C.



## Chapter 2

# BECCS in Climate Scenarios

Mariliis Lehtveer

## The Carbon Budget for 2.0°C and 1.5°C

A carbon budget is the maximum amount of carbon that can be released into the atmosphere while maintaining a reasonable chance of staying below a given temperature rise. In energy system models, this budget is defined as the amount of cumulative CO<sub>2</sub> emissions over a given period that keeps the global average temperature increase under a specific threshold with a certain probability, the so-called threshold avoidance budget, but other definitions of carbon budget exist. In its latest assessment report, the Fifth Assessment Report (AR5), the IPCC estimated the threshold avoidance budget to be 630–1180 GtCO<sub>2</sub> for >66% likelihood of achieving the 2°C emission target between 2011 and 2100 and 90–310 GtCO<sub>2</sub> for >50% likelihood of achieving the 1.5°C target in the same period. Since the beginning of 2011, about 280 GtCO<sub>2</sub> have already been emitted from land-use/cover changes, fossil fuel combustion, and cement production, reducing these budgets (Le Quéré et al., 2018). If global emissions were kept at the 2017 level, approximately 41 GtCO<sub>2</sub>/yr, remaining budget would be depleted within 8–22 years for the 2°C target and would already be depleted for 1.5°C.

The recently released IPCC special report evaluating pathways to 1.5°C target increased the initially estimated carbon budget to approximately 690–1030 GtCO<sub>2</sub> for >66% likelihood of achieving the 2°C target between 2016 and 2100 and to approximately 370–520 GtCO<sub>2</sub> for >50% likelihood of achieving 1.5°C in the same period. With about 80 GtCO<sub>2</sub> emitted in 2016–2017, this would allow continuing emissions at the 2017 level for 15–23 years and 7–11 years, respectively. In comparison, the typical lifetime of a power plant is 25–30 years,

meaning that changes in the energy system must be rapid to reach zero emissions globally in the near term so that the budget will not be exceeded. Massive expansion of carbon-free technologies is needed, together with premature retirement of at least some of the fossil-fuel-based infrastructure (McCollum et al., 2018). Also, since the net effect of non-CO<sub>2</sub> climate forcers, such as methane, nitrous oxide, and aerosols, is expected to be positive in the future, the CO<sub>2</sub>-based budgets will be diminished even further.

Technologies that enable CO<sub>2</sub> removal from the atmosphere could compensate for near-term emissions or for emissions from sectors that are difficult to decarbonise, such as agriculture or aviation, as well as allow the pursuit of more ambitious climate targets, such as 1.5°C, which could otherwise be out of reach. Several such technologies have been proposed: bioenergy in combination with carbon capture and storage (BECCS), direct capture of CO<sub>2</sub> from air, enhanced weathering of minerals, afforestation and reforestation, as well as various manipulations of ocean or land carbon uptake. Of these technologies, BECCS has the advantage of that it can be applied to processes already present in energy system (e.g., electricity, heat, biofuels, or pulp and paper production) albeit with increased costs. However, it is important to keep in mind that negative-emission technologies are not an alternative to conventional mitigation, as emissions from the rest of the system still need to decrease sharply to meet the carbon budget.

## **Reliance on Negative Emissions for Budget Closure in Energy Scenarios**

Integrated assessment models (IAMs) combining technology-, economy-, and environment-related factors are often used while assessing different mitigation pathways of climate change. The IPCC's latest assessment report (AR5) database comprises 1184 scenarios from 31 different IAMs evaluating different energy pathways and carbon emissions trajectories over the 21<sup>st</sup> century. Fewer than 300 of these scenarios achieve a concentration target of 450 ppm of CO<sub>2</sub> by 2100 and are considered to have a good chance of achieving the 2.0°C goal. Most AR5 scenarios were provided by model comparison projects, several of which

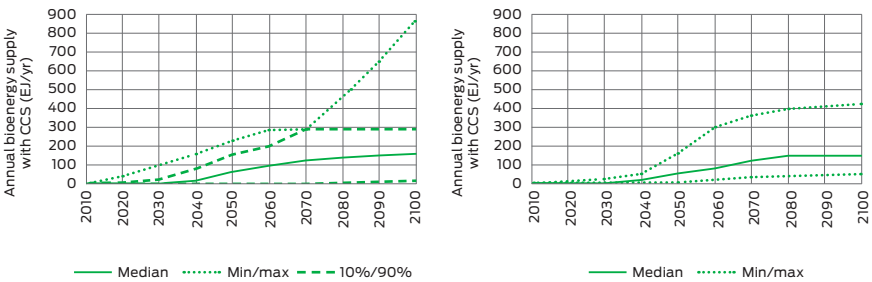
ended in 2009, making many AR5 scenarios around ten years old.

Recently, a new scenario framework has been developed, taking into account different possible socioeconomic development trajectories the world could take—the so-called Shared Socioeconomic Pathway (SSP) framework (O'Neill et al., 2014). Combining these SSP trajectories with Representative Concentration Pathways (RCPs), i.e. trajectories for greenhouse gas emissions, allows the estimation of different climate outcomes. The SSP database assembles newer global energy system scenarios that account for recent technological developments, for example, in solar and wind power. In addition, all IAMs used to produce current SSP scenarios have integrated land-use models that improve the representation of biomass availability under varying demographic and agricultural conditions (Popp et al., 2017). SSP scenario database currently holds 105 scenarios from six IAMs, of which 18 are compatible with a good chance of keeping average global warming under 2°C.

The SSP framework looks at five possible socioeconomic world development pathways. SSP1 depicts a world with low mitigation and adaptation challenges due to fast-paced sustainability processes, rapid technological development, and land productivity. SSP2, an intermediate pathway between SSP1 and SSP3, has moderate challenges. SSP3 represents a world with high challenges due to rapid population growth, slow technological change, regional fragmentation, and unfavorable institutional developments. In this world, stringent mitigation targets cannot be reached. SSP4 is characterized by high adaptation and low mitigation challenges in a world where the development and deployment of mitigation technologies is rapid in high-income regions, yet low-income regions are left highly vulnerable to the impacts of climate change. SSP5 depicts a world with high mitigation and low adaptation challenges due to a lack of climate policies and low investment in mitigation technologies, yet with high investment in human capital that results in slower population growth, stronger institutions, and, thus, higher adaptive capacity (O'Neill et al., 2014). The SSP scenarios also provide information about five world regions: 1) OECD, comprising the OECD 90 and EU Member States and candidates; 2) REF, comprising countries from the reforming economies of Eastern Europe and the former Soviet Union; 3)

ASIA, comprising most Asian countries with the exception of the Middle Eastern countries, Japan, and former Asian Soviet states; 4) MAF, comprising the countries of the Middle East and Africa; and 5) LAM, comprising the countries of Latin America and the Caribbean. The scenarios in the AR5 database, however, are presented at the global level and socioeconomic developments are not specified.

**Figure 2-1 | Bioenergy with carbon capture and storage (BECCS) in the primary energy supply in the AR5 (left) and SSP (right) scenarios.**



Note: The AR5 database can be accessed at <https://tntcat.iiasa.ac.at/AR5DB> and the SSP database at <https://tntcat.iiasa.ac.at/SspDb>.

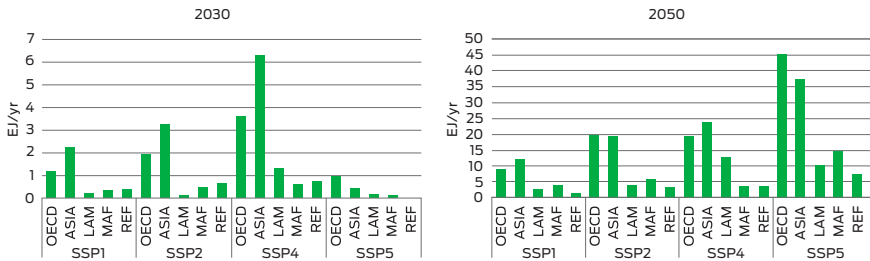
As shown in Figure 2-1, BECCS is deployed in all of the new SSP scenarios compatible with RCP 2.6 W/m<sup>2</sup> (i.e., likely to achieve the 2.0°C goal) and in over 90% of the AR5 scenarios that have a carbon concentration of 450 ppm or lower by the end of the century. While there have been only small changes in the AR5 and SSP median values (e.g., 50 EJ/yr by 2050 in the AR5 scenarios vs. 53 EJ/yr in the SSP scenarios), the ranges of use of BECCS have narrowed significantly in the latter, from 0–866 EJ/yr by 2100 in the AR5 scenarios to 47–417 EJ/yr in the SSP scenarios. This effect can at least partially be attributed to the use of fewer scenarios. Most of the scenarios in both databases see BECCS expanding between 2030 and 2040, making increased contributions over the century. A large share of BECCS is used in the electricity sector in AR5 scenarios - in the median case 8 EJ of electricity is produced with BECCS at 2050 globally. Assuming 35% efficiency in conversion from primary energy to electricity, this trans-

lates to 23 EJ of primary energy, i.e., approximately 46% of all primary energy from biomass with CCS. More detailed division among other sectors is unavailable in the database and even less detail is provided for the SSP scenarios.

The average level of BECCS used under the different socioeconomic conditions and in the different regions is illustrated in Figure 2-2. Again, BECCS is employed in all regions and under all socioeconomic conditions. The sharpest increase in BECCS deployment occurs in SSP5, in which mitigation efforts are delayed in contrast with SSP1, which prioritizes mitigation. This is compatible with previous literature asserting that delays in mitigation efforts increase the need for and importance of large-scale use of negative emission technologies late in the 21st century, to compensate for the earlier temperature overshoot (Azar et al., 2013; Fuss et al., 2014). OECD and ASIA stand out as the regions with the most BECCS employed, with values of 2–59 EJ/yr in terms of primary energy by 2050 in OECD and 2–54 EJ/yr in ASIA.

Higher regional disaggregation is unavailable in the above-mentioned databases. However, the AMPERE model comparison project conducted between 2011 and 2014 that also contributed to the AR5 scenarios, specifically assesses mitigation pathways for Europe (Schwanitz et al., 2015). The project database contains information about BECCS use in EU27 in 174 scenarios with a stringent carbon target (450 ppm) provided by nine IAMs. The median deployment of BECCS is 5 EJ at 2050 in primary energy terms, of which about 2 EJ are used in electricity production resulting in 0.75 EJ electrical energy. In comparison, the electrical energy available for final consumption was 10 EJ at 2016 in EU28.

**Figure 2-2 | Average deployment of BECCS in the SSPs and regions.**



Note: the scales differ between the graphs.

## Common Model Assumptions

Of the possible negative-emission technologies, IAMs have mostly focused on BECCS together with re- and afforestation, while a few also include direct air capture. Sectoral coverage comprises electricity and heat in power stations, hydrogen generation, and sometimes generation of transport fuels and bioplastics (Smith et al., 2015). While modelling different negative emission technologies, the focus is on their technical and economic aspects and the socio-political factors are often neglected.

Investment decisions in IAMs are made assuming long-term, stable, and high carbon prices; perfect knowledge of technology costs; and perfect coordination in international supply chains. IAMs give less weight to future costs via discounting. In effect, they assume that the discounted cost of BECCS in future decades is less than the cost of deep mitigation today. Furthermore, the future availability of BECCS is not uncertain in the models. Scenarios are typically run with the BECCS option on or off, meaning that the model can adjust to the situation and find the optimal mitigation trajectory over the century. However, in practice, considerable uncertainty is involved in making investment decisions, stemming from geopolitical, technological, and social acceptance-related aspects (Peters & Geden, 2017). It has been widely argued that assumption of BECCS availability in the future leads to moral hazard (Azar et al., 2013; Fuss et al., 2014; Gough et al., 2018). If negative emissions are used to delay mitigation but they do not deliver as expected, future generations will suffer the consequences or stabilization below 2°C may be out of reach.

In the case of BECCS, the negative emissions concept is based on notion that, since CO<sub>2</sub> is absorbed from the atmosphere while biomass is growing, if the CO<sub>2</sub> produced during biomass combustion is captured and stored indefinitely, CO<sub>2</sub> can be removed from the atmosphere. Most models assume carbon-neutral production of biomass (i.e., CO<sub>2</sub> sequestered by feedstock growth = CO<sub>2</sub> released in generating energy or goods from that feedstock). This assumption allows the generation of large-scale negative emissions from BECCS. In reality, biomass may have associated emissions due to agricultural practices or soil properties that reduce or even negate the climate benefits of BECCS (Harper et al., 2018).

In addition keeping track of emissions can be complicated, especially if biomass is traded between countries. However, efforts have been made in recent years to improve the representation of biomass availability and land-use effects via the integration of dedicated land-use models (Popp et al., 2017), meaning that some of the land-use issues are modelled in SSP scenarios discussed in this chapter.

Many of the developments are also seen as globally homogenous in energy system models. For example, BECCS is generally assumed to be deployed in all regions with rather similar patterns. In reality, the diffusion can differ between regions due to various socioeconomic, resource, and technical conditions. In a survey of delegates to the UN climate change negotiations, Fridahl and Lehtveer (2018) show that there are significant differences in perceived barriers depending on the respondents' country of residence, which is explored further in chapter 3. Regional differentiation in models could be potentially increased by taking into account current investment preferences, social acceptability, existing infrastructure, level of development, and economic capacity to invest in such large-scale projects. Some efforts have been made to better represent social preferences in IAMs, notably in the transport sector (e.g., McCollum et al., 2017), but to our knowledge there are no applications to BECCS or other negative-emission technologies. Since overseas transport costs are low, it is also possible that some regions, especially ones with good wind and solar conditions, would be providers of biomass while others with more limited resources would rely on imported biomass to reduce their emissions. Thus, BECCS deployment patterns could differ regionally.

The models also treat technological potential in a narrow sense, often restricted only by biomass availability, net conversion rates and sometimes also by limited storage capacity (IEA, 2011). Technology potential can also be represented in models via different regional costs or availability of technology in different time periods. The focus is thus often on technical factors and potentials; socioeconomic readiness is not considered. Technological readiness, however, can be conceived of as a broader concept including not only technology maturity, but also the capacity to operate technologies (i.e., know-how) and the readiness of systems to supply biomass operations with raw material. From

this perspective, BECCS is a relatively complex technological system involving, when scaled up, large changes in land-use practices and technology use, as discussed in expert assessments and elsewhere (Buck, 2016; Vaughan & Gough, 2016). This indicates a need to move from narrow definitions focusing on biomass availability, conversion rates, and storage capacity to definitions factoring in other social and political aspects of technological readiness when analysing climate scenarios.

Finally, policy incentives are often implemented at the country level and are therefore difficult to include in models covering large regions comprising multiple countries having varying relationships with one another. Some of the effects can, however, be captured by the regionalized technology costs, availability, and allowed expansion rates employed in the models.

## **Alternatives to BECCS**

It is important to note that the use of BECCS in model scenarios does not necessarily indicate that climate goals cannot be reached without it. Most models rely on a utility or cost optimization that favours the most cost-effective technology. Therefore, a separate analysis that excludes BECCS as an option is needed to assess the feasibility of achieving climate goals without BECCS. It is thus unclear from just looking at the scenarios in the AR5 and SSP databases whether BECCS is necessary to achieve the 2.0°C target, but excluding it would certainly increase the projected cost of reaching the goal in the models (Azar et al., 2013).

Alternatives to BECCS use have recently been explored. Grubler et al. (2018) envisioned a pathway that reduces energy demand by about 40% from today's level by 2050, despite rises in global population, income, and economic activity. In this scenario, high energy efficiency is achieved via high electrification rates in all sectors, digitalisation for improved coordination, shared solutions for transport, retrofitting existing building stock and applying high energy standards to new buildings, changes in income-related diet developments such as meat intake, and reduced material needs in industrial production. Although this scenario is technically feasible, it would require strong and potentially unpopular policies and may thus be as hard to achieve as large-scale BECCS deployment.



Besides efficiency improvements and demand reductions, other negative-emission technologies could possibly at least partially replace BECCS. A recent review by Fuss et al. (2018) estimated carbon removal potential for several such options to be up to 5 GtCO<sub>2</sub>/yr. The study also concluded that it is unlikely that a single negative-emission technology will be able to sustainably provide the rates of carbon uptake described in IAM scenarios consistent with the 1.5°C target.

## Summary and conclusions

Limiting carbon emissions to the estimated budget for keeping the average global warming under 1.5°C or 2°C requires rapid reduction of emissions. Negative emissions could possibly aid this transition by compensating for near-term emissions from the energy system and for emissions from difficult-to-decarbonize sectors as well as help us pursue more ambitious climate targets, such as 1.5°C. BECCS can be considered a key technology for meeting both the 2°C and 1.5°C goals in the IAM global energy scenarios calling for median global deployment of about 50 EJ/yr of primary biomass with BECCS by 2050. Nearly half of the primary energy with BECCS in these scenarios is deployed in the electricity sector. Regionally, OECD and Asia are expected to have the largest BECCS deployment, with the Europe-focused AMPERE study foreseeing about 5 EJ of BECCS in primary energy terms in EU27 by 2050 with about 2 EJ of it being deployed in the electricity sector. However, IAMs mainly consider techno-economic potentials, taking limited account of socioeconomic factors that may facilitate or hinder BECCS deployment.

## Chapter 3

# Views of BECCS Among Modelers and Policymakers

Simon Haikola, Anders Hansson, Mathias Fridahl

**Since the adoption of the Paris Agreement**, intense scientific and political debate has emerged over the feasibility of climate scenarios whose goal is to limit global warming to well below 2.0°C. The debate centers on the climate scenarios' reliance on negative-emission technologies, such as bioenergy with carbon capture and storage (BECCS), to achieve the goal (see chapter 2).

Geden (2015, 2018) has argued that modelers “are being pressured to extend their models and options for delivering mitigation later” (2015, p. 28), not least by including BECCS in their models' technology portfolios. From Geden's (2015, 2018) perspective, these scenarios have become increasingly politically informed. While radical mitigation has been deferred, climate policymakers have clutched onto the theoretical hope that the temperature goal is still within reach without conducting an appropriate reality check. The inclusion of BECCS in models may, Geden (2015, 2018) has argued, create a false sense of optimism and undermine the integrity of climate science. In support of Geden's observations, Beck and Mahony (2018) traced the vast deployment of BECCS to the adoption of Representative Concentration Pathways (RCPs) as a model logic in the IPCC's Fifth Assessment Report. In their view, modeling that targets a fixed end-point instead of open-ended modeling from a baseline has opened the way for unrealistic and increasingly speculative results.

Besides the increasing political influence, discussions have revolved around whether the models rest on unrealistic or arbitrary assumptions concerning, for example, land availability, speed of deployment, and regulatory frameworks,

and consequently project a far too massive deployment of BECCS (Anderson & Peters, 2016; Fuss et al., 2014). This relates to a critical debate in the modeling community about the uncertainties, inconsistencies, and choices associated with integrated assessment models (IAMs), which leads us closer to the core of this chapter. First, however, some important comments on IAMs are in order. IAMs are models that integrate and link the energy, economic, and climate systems with the explicit aim of presenting results of high policy relevance, which may explain why they have gained a prominent position in climate science and the IPCC. IAMs are distinguished from the models used in conventional disciplinary research both by their purpose of informing decision making and by their interdisciplinary character, as they integrate physical, biological, economic, and social sciences.

Based on interviews with 21 researchers involved in integrated assessment modeling and a survey of 2500 delegates to UN climate change conferences in 2015–2017, this chapter discusses the policymakers' views of the prioritization of BECCS for investments and the researchers' understandings of uncertainty in modeling. This allows us to conclude with some words on the heated discussions of the relationship between modeling and climate policymaking mentioned above.

The chapter begins with a presentation and discussion of the survey results. The researchers' views of integrated assessment modeling are then discussed, after which some conclusions are drawn from the survey and interviews.

## **Policymakers' investment preferences**

The IAMs provide technology-cost optimized climate scenarios often assuming a globally homogeneous price on carbon, an assumption far from current reality. In 2018, 45 countries put substantially varying prices on carbon, ranging from below EUR 1 in Poland and Mexico to above EUR 120 for certain sectors in Sweden (World Bank, 2018). Furthermore, biogenic emissions are often exempted from these pricing schemes, contrary to model assumptions.

In making investment decisions about BECCS, capital as well as operational expenditures are weighed against potential revenues. As BECCS provides no added value but mitigation, revenues are pending, awaiting policy instruments capable of providing market pull for BECCS. As this is currently lacking globally (see chapter 6), investments are awaiting business models that can develop a premium market segment encouraging voluntary customer compensation for negative emissions. As presented in chapter 7, under such circumstances and given the high capital and operational expenditures associated with BECCS, the technology is unlikely to materialize at any substantial level.

After examining 2500 survey responses<sup>1</sup> on how delegates to UN climate change conferences would like to prioritize BECCS for investments in the climate scenarios, two observations are notable:

First, BECCS investments are given a lower priority than other technologies for low-carbon development by all types of actors from all world regions. Preferences depend on both actor type and country of origin, with governmental actors being slightly more positive and environmental actors slightly more negative, and with respondents residing in regions with a higher theoretical potential for BECCS being more in favor of BECCS investments than are respondents residing in regions with lower potential.

Second, the low prioritization of BECCS vis-à-vis other mitigation technologies is at odds with the high magnitude of BECCS deployment assumed in climate scenarios, in order to meet the Paris Agreement's temperature goals.

Prioritizing other mitigation technologies is also in line with actual practice. Investments in renewable energy, for example, far exceed investments in BECCS. However, such investments are not occurring at scales that exceed those assumed in the climate scenarios. Quite the opposite is the case. An indication of this is provided both by continuously increasing global emissions and by the collective ambition of countries' Nationally Determined Contributions (NDCs) to the Paris Agreement. The NDCs point toward a massive emission gap in 2030, between the climate scenarios' cost-optimized pathways to limit-

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<sup>1</sup> The survey design is based on Likert-style response options, with data collected at UN climate conferences between June 2015 and December 2017. The data type requires non-parametric statistical analysis; Kruskal-Wallis and appropriate post-hoc tests have been applied. For details on method, see Fridahl and Lehtveer (2018).

ing warming to 2.0–1.5°C and the countries' pledges (UNEP, 2017).

In this connection, Anderson and Peters (2016) warned of the moral hazard involved in deferring contemporary mitigation actions based on assuming that BECCS will deliver negative emissions in the future. Governments across the world owe their constituencies an answer as to how they can both agree to an ambitious temperature goal and fail to present mitigation plans that are even remotely aligned with the climate scenarios. When evaluating the NDCs against climate scenarios, one should keep in mind that the scenarios in turn rest on assumed future deployment of BECCS. If today's mitigation potential is not utilized due to hopes for future BECCS deployment, and it turns out that BECCS fails, future generations will find their options severely circumscribed.

Government actors' low prioritization of BECCS could be advisable if today's mitigation actions and the near-term NDCs were on track to outperform the climate scenarios, allowing relaxed reliance on the future delivery of BECCS. However, such is not the case. As mentioned, NDCs underperform dramatically rather than outperform, exacerbating the reliance on the future delivery of BECCS to resolve the climate crisis.

This does not mean that BECCS R&D should be stopped. Ongoing technical and policy development, as well as public deliberations to understand conflicts and mediate among divergent views, are necessary. In the end, BECCS may or may not prove able to help resolve the mitigation dilemma. However, as noted by Anderson and Peters (2016), as there is currently no way of knowing this, hopes for future BECCS deployment should not be used to defer exploration of alternatives, including contemporary radical mitigation actions through technical diffusion, development, and lifestyle changes. The inconsistency involved in simultaneously failing to achieve ambitious near-term targets and lack of interest in investing in BECCS R&D for mid-term deployment and long-term upscaling is intriguing. In the following sections, we delve deeper into the core of these complexities by presenting modelers' views of the management of BECCS in IAMs.

## Researchers' views of uncertainty, modeling, and policy development

The coming sections are based on interviews with 21 researchers, conducted in 2017 and 2018, which started by addressing the critical public and scientific debate on IAMs that arose around the time of COP 21 in Paris, as described above. The informants were either working in or around what we call the IAM community or had experience of modeling and were participating actively in the scientific and public debate on IAMs.

Much of the criticism of how IAMs deploy negative-emission technologies (NETs), and especially BECCS, is anchored in the perception of integrated assessment modeling as a discipline dominated by economists lacking deeper understanding of the natural scientific results used as data in the models. However, while economists do figure prominently in it, the IAM community nowadays includes, and is defended by, several researchers who share scientific backgrounds with those criticizing IAMs for lacking natural-science validity. The inter-scientific debate about uncertainty in IAMs should therefore not be understood as a debate between disciplines, but rather as a debate between epistemic discourses. In a simplified but functional distinction, we can separate these into two main discourses: one *critical* of and one *supportive* of the contribution of IAMs to climate science and policy. We will call the former “the critical discourse”, and the latter ‘the IAM discourse’. Each discourse determines how researchers view the relationship between, on one hand, *the hypothetical worlds* of models and, on the other hand, *the real worlds of atmospheric, biophysical, social, and policymaking processes*. Both discourses revolve around three key, inter-related dimensions: 1) the management of uncertainty in models, 2) realism, and 3) performativity. In the following three sections, we will describe each of these dimensions. It should be noted that each discourse are idealized representations, constructed by us, of a multitude of sometimes inconsistent statements, and that several informants voiced opinions that placed them in both discourses. Our presentation of the discussions as belonging to two separate discourses is a way of making sense of the empirical material data in a way that generalizes yet is faithful to it.

## Managing uncertainty

The view of how uncertainty is and should be managed in climate modeling separates integrated assessment modelers from a majority of the other informants. For the latter, the complexity of each of the social and natural processes included in the modeling scenarios, let alone their interactions, calls for modeling that is disaggregated and “pure,” in that the number of variables is strictly limited so the results will be decipherable. Complex modeling is dependent on results being retraceable to their origins through retrospective analysis. Simply stated, with each additional variable, the range of possible outcomes increases, hence the difficulty of qualitatively determining the logic behind the results. For many who work outside the IAM community, IAMs are particularly prone to uncertainty in qualitative assessment because of the ambition to incorporate a wide range of variables from multiple scientific areas. One physical engineering researcher described his experience working with the IAM community as follows:

It’s quite amazing to see how the physicists just don’t question what the economists say. There are some scenarios, some models, and the physicists just take the results and say, “Ok, let’s do that!” No questioning, no criticizing. It has nothing to do with intellectual capacity but with time. The same phenomenon is apparent in the literature, where you can see different communities using radically different methods to answer the same questions, in a way that makes it difficult to compare or communicate.

In this view, not only does the sheer number of variables render uncertainty nearly unmanageable, but the disciplinary boundaries create new uncertainties unique to IAMs. Furthermore, the desire to include socioeconomic dimensions in scenarios by exploring possible trajectories of political, economic, and technological development invites suspicion from many who argue that the uncertainties inherent to such processes make them fundamentally impossible to quantify.

The dominant response to such criticism from the other discourse is not to simply refute the claims of uncertainty associated with increasing complexity. Instead, uncertainty is embraced on the premise that there is simply no other way to conduct a scientific analysis of such interrelated and highly complex processes. In this view, the criticism about inadequate uncertainty management is misplaced because it wrongly supposes that IAMs strive to make long-term scientific predictions, something that should be reserved for short-term, low-stakes operations such as weather forecasting. Because the future is inherently unknowable, prognoses projecting any further than the immediate future are guesswork. However, that does not mean that the future must remain unexplored, and the only way to do that in a scientifically legitimate way is to increase the number of model runs, increase the variability in parameter setting, and from the wide range of results assess what seems plausible and what does not. As one integrated assessment modeler put it: “You shouldn’t make only totally realistic scenarios, because who knows what the climate will be like in the future?”

Within the IAM discourse, a sharp distinction is therefore made between the business of hypotheticals and the business of predictions, and the message is clear that integrated assessment modelers deal only in the former. Evidently, this is a distinction that entails both limitations and a certain amount of freedom. While it precludes the possibility of making specific knowledge claims, it also opens up the possibility of exploring, in the words of one integrated assessment modeler, the “What ifs?”

In this approach to climate science we can identify an argument that different disciplines require different strategies for managing uncertainty, and that what works for one does not necessarily work for another. The reductionist way of minimizing uncertainty by “keeping it pure,” as many natural scientists outside the IAM community advocate, is unworkable for the purpose of evaluating complex, interconnected social and natural processes. In this view, both strategies are justified, and both are crucial to supplying policymakers with legitimate scientific advice.



## Realism

In the critical discourse, the question of realism is central to evaluating the usefulness of models. Many critics agree that IAMs serve a different purpose from other types of advanced climate models and that this may sometimes justify simplifications of a kind that would be deemed unscientific in other disciplines. However, as IAMs are becoming increasingly complex, they reach a point where they become detached from the real-world processes that they are modeling. One energy systems modeler voiced a common opinion:

I'm concerned that everything becomes so focused on modeling results that are totally theoretical and detached from reality ... I assume that every value [in an IAM] by itself has an objective foundation, but the end result may still lack realism.

This echoes the harsh verdict of economist Robert Pindyck (2013), that IAMs are “close to useless as tools for policy analysis.” Some critical researchers further argue that the complex interactions between processes in IAMs are, in fact, merely a superstructure covering a rather limited set of basic assumptions concerning economics and technological development. From this perspective, the main problem with the models’ detachment from reality lies here, in their fundamental assumptions. The models’ complexity is a secondary problem, in that it hides the flawed underlying principles. As one critic put it, “The boundaries are hugely subjective, so what we get is objective analysis within subjective, and hugely simplistic, boundaries.”

More common than outright dismissal based on the models’ perceived lack of realism, however, is a view that the IAM field has reached saturation point. While IAMs could plausibly serve an experimental and mainly heuristic purpose in visualizing different developmental trajectories, the current mass production of IAM scenarios is meaningless, given their lack of anchoring in the real world. According to critics, the proliferation of scientific papers on IAM results indicates purpose-drift within the IAM community, a loss of its *raison d’être*.

Within the IAM discourse, however, the accusations of unrealistic scenar-

io-making miss their target, once again because they are premised on a mistaken assumption about the logic and purpose of IAMs. Lack of realism in research is only a problem insofar as the driving force is to make as exact a replica of reality as possible, which in modeling terms often translates into maximizing the model's resolution. In the view of many integrated assessment modelers, that is a functional and legitimate logic for modeling activities aimed at capturing in detail the workings of primary atmospheric and biophysical processes, but it is unworkable for the broader thrust of integrated assessment modeling. You cannot seek to copy the world, explained one integrated assessment modeler, because all you have then is a mere double. Instead, what integrated assessment modelers strive for is "to understand the behavior of the system," as one modeler explained, in other words, why their models yield certain results and how these results relate to reality. From this standpoint, the task is to produce speculative scenarios—sometimes wildly unrealistic ones—in order to understand how the models work, and to use the findings from these imaginary worlds to inform policymaking in the real world.

The concept of realism has slightly different connotations in the two discourses. In the critical discourse, the concept is anchored to the past, to the historical record of scientific data, and premised on the ability of models to accurately reconstruct natural processes. In the IAM discourse, realism is fundamentally about being able to say something important about the future, about making sense of the interactions of complex processes to create a meaningful message. Accordingly, how the models are used to create a message is the third key aspect of these two discourses, and we turn to this in the following.

## **Performativity**

The question of usefulness raised by Pindyck (2013) has no direct relevance to the issue of how IAM results come to matter (i.e., performativity). If the results are deemed useful by policymakers they are likely to be used, regardless of their scientific validity. A key feature of the critical discourse is the claim of moral hazard mentioned in this chapter's introduction, i.e., that IAMs make the scientifically faulty assumption that BECCS could work on a large scale and thereby

risk justifying delayed mitigation in the eyes of policymakers. According to many critics, IAMs are something far worse than useless: they are useful for dangerous purposes.

In the IAM discourse, the moral hazard claim is opposed to the argument that any mitigation strategy must be based on the visualization of viable alternatives. If the technological development of BECCS is ever to be possible, it must first become part of the policy discussion, so the main function of IAMs is to illustrate to policymakers what might be technologically possible if it were forcefully pursued. Far from engendering moral hazard, in other words, the presentation of BECCS to policymakers through IAM scenarios is a prerequisite for any technological push whatsoever. This argument is related to the claim that IAMs are only hypotheticals and not predictions, and that this fact is clearly communicated to policymakers. However, in contrast, several integrated assessment modelers also express doubt as to the possibility of communicating uncertainties to external communities.

The last point is at the center of the critical discourse. According to many critics, the problem of the misappropriation of results is not so much about flawed communication, but that most IAM studies addressing BECCS create the impression of an alternative development trajectory that simply does not exist. Integrated assessment modelers' claim of transparency about the hypothetical nature of their models fails, according to critics, to take into account how scientific information is actually received and processed in the policy realm. One researcher, for example, argued that “[integrated assessment] modelers continually insist that policymakers are aware of uncertainties [concerning BECCS], but when I talk to politicians, they always say they haven’t got a clue.”

In this way, the critical discourse also highlights contradictions in the IAM discourse of which the parties to that discourse may or may not be aware, but that nevertheless become part of a process of self-reflection in the way the IAM community presents itself outwardly and reasons about its professional legitimacy. In the following, we discuss how some of these contradictions appear in the IAM discourse.

## **Contradictions in the self-representation of integrated assessment modelers**

The IAM discourse is very reflexive as concerns the role of IAMs in climate science production and policymaking. Without a doubt, this reflexivity is a result both of years of intra-disciplinary discussion about methodological issues and of criticism leveled from outside the community (see Beck & Krueger, 2016; Creutzig et al., 2014; Fuss et al., 2014; Geden, 2015, 2018). Unsurprisingly, the criticism has grown in intensity in step with the increasing attention paid to IAMs in climate science and IPCC work. As a result of this growing criticism as well as growing influence, certain contradictions can be seen in the self-representation of integrated assessment modelers.

These contradictions pertain to the perception that integrated assessment modeling is a scientific operation with certain unique preconditions and sources of legitimacy, and to the pervasive notion within the IAM discourse that it is being misunderstood and misrepresented on the outside. The claim of being able to make scientific sense of highly complex, interrelated social and natural processes means, according to this view of integrated assessment modeling, that special forms of uncertainty management are justified. The legitimacy of IAMs, in the dominant perspective in the IAM discourse, lies not primarily in scientific verifiability but in policy relevance.

This core mission statement is somewhat contradictory, in that it is simultaneously both highly ambitious and modest. Integrated assessment modelers are quick to insist that they are dealing in hypotheticals, not in predictions, and that their results must always be treated accordingly. At the same time, this reiterated modesty stands in contrast to the core idea of being performative, of wielding influence, of speaking science to power. There is an obvious point in moderating one's truth claims under intense criticism, but perhaps the appeal to caution is also a response from the IAM community to its success in becoming policy relevant.

Likewise, this modesty can be seen to stand in contrast to the global, encompassing scope of integrated assessment modeling. Striving to say something about everything, the IAM community has understandably been viewed with

suspicion by more traditional scientific disciplines, in which the methodological imperative is to limit rather than expand the number of variables in order to reduce uncertainty. The response from one integrated assessment modeler that members of the IAM community do not and cannot “aim to copy the world, because then all you have is a double” could be understood as responding to such outside perceptions. While the statement amounts to a reservation, it also indicates that the idea of “doubling” the world is present in the IAM discourse, if only as an ideational point of reference. Hence, there is a felt imperative to disavow any such claims, and the quote can be interpreted as a response to what is perceived in the IAM community as the image it projects outwards. Yet the disavowal of pretensions to universalistic claims is precarious, because when the researcher cited above speaks of “understanding the behavior of the system,” he is speaking not merely of the model system, but simultaneously of the world system mimicked by the model. Here is the ambiguity at the center of the IAM discourse, about what kinds of truth claims are made possible by the models, and what kinds are precluded.

This ambiguity can also explain the contradictory status in the IAM discourse of model results as both transparent and complex, as both easily communicated and esoteric explorations of imaginary worlds. If there is ambiguity even in the IAM discourse as to what kind of knowledge the models produce, then it is understandable if there is some discomfort about what happens when this ambiguous knowledge crosses institutional boundaries and, perhaps most importantly, enters the world of policymaking. In our conclusions, we accordingly further reflect on the relationship between IAMs and policymaking.

## Conclusions

Contradictory perceptions in the IAM discourse indicate some discomfort among the modelers themselves with the modeling activity’s boundary position between science and policy. The obvious disconnect between policymaker perceptions and the development trajectories sketched by the low-warming

IAM-derived scenarios prompts some concluding reflections on these contradictions, and on a certain contradiction in the critical discourse. On one hand, the almost complete lack of political initiatives to deploy BECCS on a European level can be viewed as validating the opinion that the IAMs that incorporate large-scale BECCS deployment are detached from reality and therefore should not be considered legitimate scientific input to policy. On the other hand, and as Bellamy argues in chapter 5 of this book, the political inaction seems to contradict the argument that IAM BECCS scenarios could come to be wielded as justification for postponing mitigation.

The lack of political action in relation to BECCS makes it relevant to question whether IAMs really do have the policy influence striven for by those who produce them and assumed by those who regard them as engendering moral hazard. This raises the question of how much more knowledge can be gained from exploring imaginary worlds when the real world of policymaking is so clearly lagging behind and, more importantly, what difference such knowledge can make. The scientific certainty or consensus is convincing enough to justify immediate deep global emission reductions. The process of constructing cost- and time-optimized scenarios will always harbour fundamental uncertainties, and we would argue it is highly unlikely that such uncertainties will be reduced through the continued proliferation of IAM scenarios. Further exploration – or construction – of imaginary worlds through IAMs would either be policy irrelevant or, worse, hold out the promise of uncertainty reduction through their ambiguous knowledge claims. Climate models will always be precariously positioned between exploring and colonizing the future, and even if integrated assessment modellers are clearly aware of this balancing act, there is reason to ask how much more could be gained by exploring the as yet purely hypothetical realm of NETs. If and when exploration becomes colonizing, IAMs will, as Geden (2018) has warned, prolong negotiations and justify further scientific investigation instead of political action.

## Chapter 4

# European and Swedish Point Sources of Biogenic Carbon Dioxide

Anton Arbman Hansing and Mathias Fridahl

**Acknowledging the climate scenarios'** future deployment of BECCS in Europe and modelers' questions as to the feasibility of implementing the level of BECCS proposed in the scenarios, this chapter provides a crude estimate of the existing European potential for BECCS.

This potential is estimated through mapping point sources of biogenic CO<sub>2</sub> from three types of processes with particularly promising prospects for BECCS: production of paper and pulp, combined heat and power (CHP), and bioethanol.

The production of pulp, paper, and paperboard ("pulp and paper" for short) is very energy intensive and generates considerable CO<sub>2</sub> emissions. Due to improved energy efficiency and a switch from fossil fuels to in-house biomass-based fuels, a large proportion of these CO<sub>2</sub> emissions are biogenic (Sun et al., 2018). This, in combination with the fact that the emissions are often concentrated in just a few large production plants, makes these industries promising for BECCS deployment.

CHP is one of the most commonly discussed target industries for both fossil CCS and BECCS (Gough & Upham, 2011; Kindermann et al., 2014). The industry has several potential advantages for CCS, such as high demand for electricity and heat that is unlikely to decline, and centralized production, with large plants often emitting several megatonnes of CO<sub>2</sub> annually.

The relevance of a particular CHP facility to BECCS depends primarily on the

fuel combusted at the facility. Facilities can be divided into fossil, biomass, and waste CHP plants. These categories are not mutually exclusive, as many plants can indeed alternate between fuels in the short and long terms (Emmenegger et al., 2012; Johnke, 2003; Mohn et al., 2008).

A third economic activity often seen as promising for BECCS is large-scale bioethanol production (Pacca et al., 2016). The primary reason for this is process related: renewable ethanol production requires biomass fermentation. During fermentation, highly concentrated streams of CO<sub>2</sub> are released. The purity of these CO<sub>2</sub> streams, often reaching 99% volume concentration (Pacca et al., 2016), reduces the need for expensive carbon separation infrastructure. For this reason, ethanol production is often seen as “low-hanging fruit” in the context of BECCS.

This chapter explores crude methodologies for mapping the scale and geographical concentration of biogenic CO<sub>2</sub> emissions from pulp and paper, CHP, and bioethanol production in the EU-28. The results reveal large European potential in the paper and pulp sector. That this potential is high in the Nordic countries is well established (Grönkvist et al., 2008). However, by combining data from different emission registries with different accounting requirements, it is possible to identify previously more hidden potentials for BECCS, for example in Portugal. For CHP and bioethanol, accounting practices, lack of data, and an inability to automate dataset comparison make it harder to map point sources of biogenic CO<sub>2</sub> from these sectors. A crude estimate is provided at the European level, the method used being exemplified by a more finely grained mapping at the Swedish level. The results indicate that substantial point sources of biogenic CO<sub>2</sub> exist from these activities, but that the uncertainty of these estimates remains high. As shown by Jönsson (2011), the potential in pulp and paper are far away from potential fossil capture clusters and that storage depends heavily on the expansion of transport infrastructure.



# European Biogenic Point Sources

## Pulp and Paper

### Methodology

In this section, our goal is to combine data from the European Pollutant Release and Transfer Register (E-PRTR) and the EU Transaction Log (EUTL) to estimate the BECCS potential of the paper and pulp industry.

Facilities producing pulp and paper in the EU, Norway, Iceland, and Liechtenstein are required to report their emissions of fossil CO<sub>2</sub> to EUTL. In addition, any facility with total CO<sub>2</sub> emissions exceeding 0.1 Mt per year must report its total emissions to E-PRTR; these facilities can also voluntarily report the share of fossil CO<sub>2</sub> emissions to E-PRTR.

Neither E-PRTR nor EUTL requires that facilities explicitly report their biogenic CO<sub>2</sub> emissions. By combining these datasets, however, these emissions can be trivially calculated, as each facility must report its total emissions to E-PRTR and its non-biogenic emissions to EUTL. The biogenic emission quantity is the difference between these reported quantities, i.e., E-PRTR CO<sub>2(total)</sub> – EUTL CO<sub>2(fossil)</sub> = CO<sub>2(biogenic)</sub>.

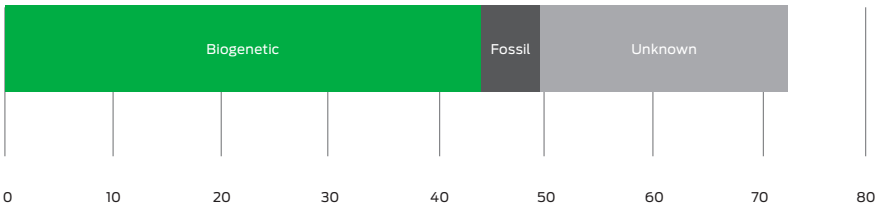
For this study, we identified all pulp and paper production facilities in the EU, Norway, Iceland, and Liechtenstein reporting more than 0.5 Mt of total CO<sub>2</sub> emissions in 2015.

### Biogenic Fraction of Pulp and Paper Industry Emissions and Data Uncertainty

Figure 4-1 shows the CO<sub>2</sub> emissions reported to E-PRTR in 2015 from production of pulp and paper. The total emissions of the two sectors combined are in the order of 70 Mt in 2015. As expected, the biogenic fraction of the CO<sub>2</sub> emissions, of known origin, is high: 89%. About one-third of the industry CO<sub>2</sub> emissions are of unreported origin.

According to E-PRTR data, 51 facilities in the pulp and paper industries reported total CO<sub>2</sub> emissions of more than 0.5 Mt in 2015. Of these, 34 facilities voluntarily reported their fossil CO<sub>2</sub> emissions, while 17 did not. All the facilities reporting both their total and fossil-fuel-based shares of emissions, enabling us

**Figure 4-1 | CO<sub>2</sub> emissions from pulp and paper reported to E-PRTR (2015).**



to calculate biogenic CO<sub>2</sub> emissions solely from E-PRTR data, were located in Sweden, Finland, Germany, or the Czech Republic. In total, 32 of these 34 facilities reported a biogenic fraction of CO<sub>2</sub> above 0.5 Mt.

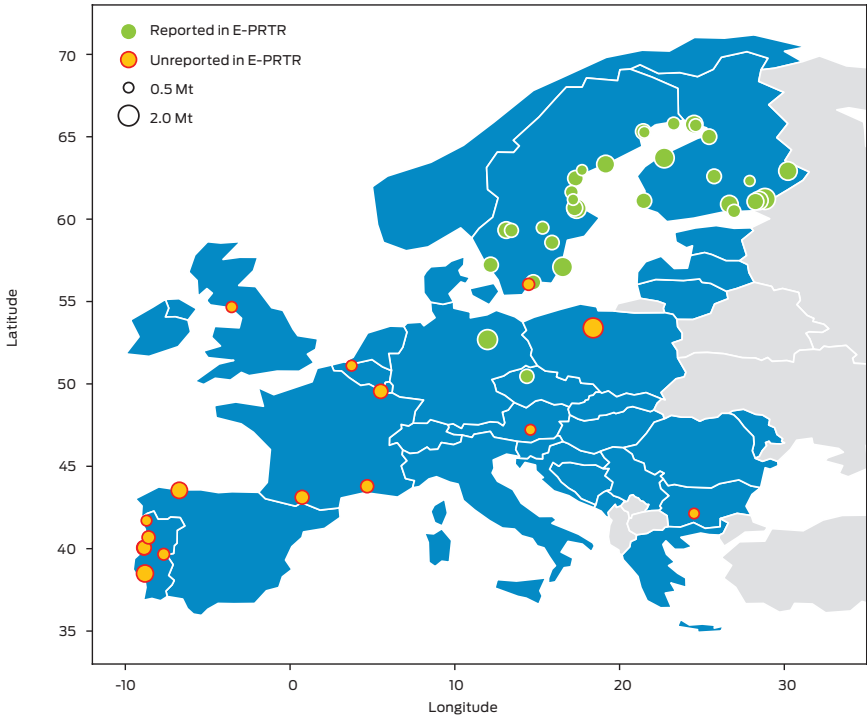
Of the 17 facilities that did not explicitly report biogenic CO<sub>2</sub> emissions, cross checking with EUTL data reveals that an additional 16 facilities had biogenic CO<sub>2</sub> emissions exceeding 0.5 Mt. As such, only two-thirds (i.e., 32) of all facilities in the pulp and paper industry that emitted more than 0.5 Mt of biogenic CO<sub>2</sub> in 2015 (i.e., 48 facilities) could be identified based on emission data reported to E-PRTR.

In summary, combining data from E-PRTR and EUTL provides insight into point sources of biogenic CO<sub>2</sub> emissions that could not be obtained by studying the two datasets in isolation. In the case of the pulp and paper industry, the analysis shows that as many as one-third of all large point-source emitters of biogenic CO<sub>2</sub> are unreported in E-PRTR. Certain promising regions for pulp and paper-based BECCS, such as the six Portuguese facilities emitting more than 5.2 Mt of biogenic CO<sub>2</sub> in 2015, are invisible to studies based only on the analysis of E-PRTR data. The result of combining the data registries is visualized in Figure 4-2.

While these results are not directly translatable to other economic activities, such as CHP or production of bioethanol, there are reasons to believe that the proportion of “hidden” large-scale emitters of biogenic CO<sub>2</sub> may also be high in other parts of the economy. One such reason is that the production of paper and pulp in Europe is disproportionately located in Nordic countries, where almost all facilities report their fossil share of total CO<sub>2</sub> emissions to E-PRTR. This

suggests that other economic activities with significant shares of biogenic CO<sub>2</sub> emissions, activities less dominated by Nordic countries, may have even larger proportions of “hidden” biogenic fractions from high-emitting facilities.

**Figure 4-2 | European paper and pulp facilities reporting more than 0.5 megatonnes of biogenic CO<sub>2</sub> emissions (2015).**



Following the assumptions of Johansson et al. (2012), this exploratory data analysis is threshold based, exclusively considering facilities emitting more than 0.5 Mt of biogenic CO<sub>2</sub> in 2015. This threshold was chosen because point sources of more than 0.5 Mt of biogenic CO<sub>2</sub> have promising positive economies of scale. However, a threshold methodology is imperfect for assessing the potential for BECCS since it disregards other significant factors, such as the proximity of facilities to geological storage sites for captured CO<sub>2</sub>, including whether they are located near the coast, facilitating sea transport of CO<sub>2</sub>.

Furthermore, importantly, smaller emitters may also be relevant to CCS if, for example, they are located within a cluster of emitters that could share CCS infrastructure (Jönsson, 2011). By including facilities reporting 0.1–0.5 Mt of biogenic CO<sub>2</sub>, an additional 23 point sources of emissions become relevant. In this analysis, locational factors were omitted for methodological reasons, primarily because there is currently no way of combining E-PRTR and EUTL data in an automated fashion. However, mapping the locations of the facilities, as is done in Figure 4-2, provides indications of substantial potential for positive economies of scale through cooperating on transport infrastructure among paper and pulp facilities in several locations.

## Heat and Power

### Methodology

First, for CHP, aggregate European emissions will be estimated using data from E-PRTR. The aggregate quantity is then divided into reported biogenic, fossil, and unknown emissions, providing a crude but educated “guesstimate” of the total European potential for BECCS in CHP production.

Second, CHP facilities reporting significant biogenic shares of total CO<sub>2</sub> emission to E-PRTR are mapped geographically. Again, the 0.5-Mt threshold specified by Johansson et al. (2012) is applied. In this analysis, locational factors are omitted for methodological reasons, primarily because it is currently impossible to combine E-PRTR and EUTL data in an automated fashion. The limited number of European pulp and paper facilities facilitates the manual merger of registry records. For the more dispersed CHP production, this task was deemed too time consuming.

Finally, we attempt to assess how well the resulting sample of facilities represents the true potential for BECCS from CHP.

## Results and Discussion

In 2015, total CO<sub>2</sub> emissions of 85.6 Mt were reported to E-PRTR from economic activities defined as “steam and air conditioning supply,”<sup>2</sup> the category primar-

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<sup>2</sup> The classification of economic activities into “Steam and air conditioning supply” or “Production of electricity” uses is based on the NACE-standard, i.e. the Statistical classification of economic activities in the European Community (nomenclature statistique des activités économiques dans la Communauté européenne).

ily covering steam-driven heat and power generation, from the EU-28, Norway, Switzerland, Iceland, and Liechtenstein. Of these reported emissions, 25.1 Mt CO<sub>2</sub> were of fossil, 12.8 Mt CO<sub>2</sub> of biogenic, and 47.7 Mt CO<sub>2</sub> of unknown origin. In other words, 34% of CO<sub>2</sub> emissions of reported origin were biogenic. Extrapolating this fraction linearly to the emissions of unreported origin—a crude methodology for estimating the European-wide potential—suggests total biogenic emissions of 29.0 Mt from CHP.

Due to the data ambiguity regarding the classification of CHP facilities, it is useful to extend the analysis to also include facilities coded as the economic activity “production of electricity.” In 2015, facilities in this category reported total CO<sub>2</sub> emissions of 933.3 Mt, with 167.5 Mt of these emissions reported as of fossil, 18.6 Mt of biogenic, and 747.2 Mt of unknown origin. Emissions of reported origins were consequently 10% biogenic. If that fraction were extrapolated to all emissions in from the economic activities electricity and steam and air conditioning supply, total biogenic emissions would be estimated to be 93.1 Mt.

Of the total emitters in these activities, five electricity and CHP plants reported biogenic emissions of more than 0.5 Mt CO<sub>2</sub> in 2015 (Table 4-1). Four of these were CHP facilities, while one, the Drax Power Station, does not appear to produce heat commercially. The cumulative biogenic emissions from these facilities were 13.4 Mt CO<sub>2</sub>. Notably, Händelöverket is the only facility on the list that uses a substantial fraction of waste as fuel. For Swedish facilities, data from 2017 are available through the Swedish Environmental Protection Agency. These data have been added in parentheses in Table 4-1. The 2017 data also indicate an additional qualifying facility exceeding the 0.5-Mt threshold: the new biomass-fired CHP facility Värtaverket.

Notably, Drax Power Station, the largest emitter on the list, has already been the target of several CCS initiatives. In 2015, the plant abandoned its GBP 1-billion plan to adopt fossil CCS, intended to capture 2 Mt of CO<sub>2</sub> annually from a coal power unit, due to a cancelled government grant (MIT, 2016). In May 2018, the company instead launched a BECCS feasibility study for its biomass units (Drax Group, 2018).

**Table 4-1 | Electricity and combined heat and power plants reporting more than 0.5 Mt biogenic CO<sub>2</sub> to the European Pollutant Release and Transfer Register in 2015.**

Facility name	Country	Economic activity (NACE-code)	Total CO <sub>2</sub> in 2015 (2017 data in parentheses) [Mt]	Biogenic CO <sub>2</sub> [Mt]	Biogenic share of total CO <sub>2</sub> [%]
Drax Power Station	United Kingdom	Production of electricity	23.40	10.20	40
Eesti Energia, Narva	Estonia	Production of electricity	1.50	1.41	94
Igelsta kraftvärmeverk	Sweden	Steam and air conditioning supply	0.68 (0.72)	0.67 (0.72)	99 (100)
Eesti Energia, Auvere	Estonia	Production of electricity	0.59	0.57	98
Händelöverket	Sweden	Steam and air conditioning supply	0.71 (0.78)	0.56 (0.61)	78 (79)
Värtaverket	Sweden	Steam and air conditioning supply	0.65 (1.87)	0.05 (1.42)	8 (76)

In summary, the European CHP industry appears to be a significant emitter of biogenic CO<sub>2</sub>. A naive estimate of the annual biogenic emissions from CHP is 29 Mt CO<sub>2</sub>, though this estimate is highly uncertain for two principal reasons:

- 1. Ambiguity in data categorization:** while most CHP plants appear to report their activity as “steam and air conditioning supply,” some are in the category “production of electricity.” Including both sets of economic activities would lead to a higher estimated potential.
- 2. Regional variability:** in countries commonly reporting biogenic emissions, this fraction varies between 4% (Germany) and 62% (Sweden). Plausibly, there is a correlation between high fractions of biogenic emissions and ambitious practices of reporting biogenic CO<sub>2</sub>. If such is the case, the estimated 29-Mt biogenic share of total CO<sub>2</sub> emissions from CHP may be too high.

Although the cumulative BECCS potential is promising, this analysis demonstrates that a large fraction of CO<sub>2</sub> emissions originates from relatively small point sources. Less than 10% of the biogenic CO<sub>2</sub> emissions reported from

activities classified in the category “steam and air conditioning supply” are from point sources of more than 0.5 Mt. This might be because a significant fraction of the emissions is from relatively small waste-to-energy facilities that are cofired with fossil and biogenic fuels, the exact proportion depending on the composition of the waste fuel. One relatively recent study of Sweden estimated the biogenic fraction of waste to be around 70% (Jones et al., 2013).

## **Bioethanol**

### **Methodology**

By combining EU statistics on ethanol production with studies of how much CO<sub>2</sub> is produced in the ethanol fermentation process, we can estimate a lower bound for the total biogenic CO<sub>2</sub> emissions originating from ethanol production in the EU-28.

Research has yet to identify a rigorous way of geographically mapping bioethanol production facilities in Europe. Due to a lack of data granularity, which will be discussed below, it is infeasible to retrieve an exhaustive list of these facilities from the E-PRTR and EUTL registries. In light of this, we exemplify the potential of BECCS in ethanol production by analyzing a sample of large member facilities from the European Renewable Ethanol Association (ePURE).

### **Results and Discussion: Cumulative Biogenic CO<sub>2</sub> Emissions from Fermentation Process**

According to data from the EU-28 Ethyl Alcohol Balance Sheet (2017), 6.14 billion liters of ethanol of agricultural origin were produced in the EU-28 in 2016. Previous studies estimate the CO<sub>2</sub> emissions from the fermentation of biomass in ethanol production at 0.75–0.80 kg per liter (Kheshgi & Prince, 2005). This indicates that the cumulative CO<sub>2</sub> emissions from ethanol fermentation in EU-28 are likely to have been 4.6–4.9 Mt in 2016.

### **Point Source Analysis: Three Facilities**

Three significant bioethanol production facilities in Europe are Alco Bio Fuel

in Ghent, Belgium, Alco Energy in Rotterdam, the Netherlands, and Lantmännen Agroetanol in Norrköping, Sweden. According to self-reported production statistics, these facilities are cumulatively responsible for about 15% (or 950 million liters) of the ethanol produced in the EU-28 (AlcoGroup, 2018; Lantmännen, 2018).

Alco Bio Fuel in Ghent reports annual bioethanol production of 240 million liters. Using the estimated fermentation emission value of 0.75–0.80 kg CO<sub>2</sub> per liter of ethanol produced, this indicates that the facility produces fermentation CO<sub>2</sub> emissions in the order of 0.18–0.19 Mt per year. According to Alco Bio Fuel’s website, 0.1 Mt CO<sub>2</sub> is annually being used for soft drinks, food packaging, and industrial applications (AlcoGroup, 2018).

Alco Energy in Rotterdam reports annual bioethanol production of 480 million liters. Given the previous assumptions, fermentation CO<sub>2</sub> emissions from this would equal 0.36–0.38 Mt per year. The facility currently delivers 0.3 Mt CO<sub>2</sub> per year to greenhouses (AlcoGroup, 2018).

Lantmännen Agroetanol in Norrköping produces 230 million liters of ethanol annually, representing estimated CO<sub>2</sub> emissions from fermentation of 0.17–0.18 Mt per year. These emissions are currently being captured and utilized by the Swedish food industry (Lantmännen, 2018).

These results indicate that the cumulative biogenic CO<sub>2</sub> emissions from the fermentation process alone are large enough to make the ethanol promising for BECCS in the EU-28. This potential is likely to increase if other, more diffuse CO<sub>2</sub> emissions from the production process are accounted for and if European policy incentives for biofuels develop further, which is to be expected.

Unfortunately, E-PRTR and EUTL data provide little help in mapping point-source emissions of biogenic CO<sub>2</sub> from the ethanol industry, for two reasons:

1. Ethanol production is not a well-defined activity category in either dataset, making it difficult to identify ethanol facilities. Activities reported by ethanol production facilities include manufacture of (i) organic chemicals, (ii) inorganic chemicals, and (iii) other chemical products.



2. Large ethanol production facilities are already capturing and selling their CO<sub>2</sub> emissions for use in soft drinks, food packaging, and other industrial processes (AlcoGroup, 2018; Lantmännen, 2018). In practice, this means that the CO<sub>2</sub> is not emitted at the production facilities, and consequently is not included in the facilities' reports to E-PRTR. Little data are available on the extent of this practice.

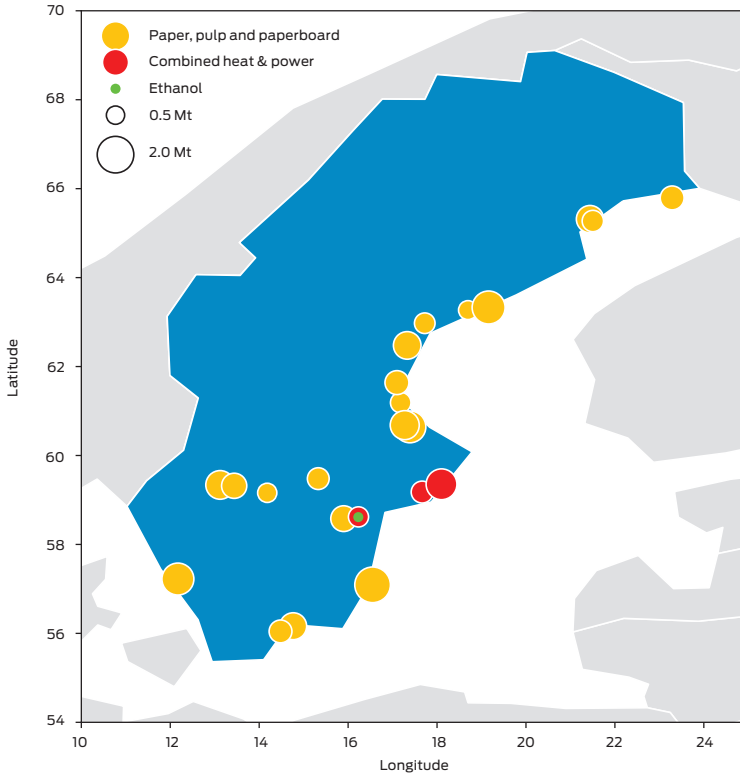
For these reasons, to the best of our knowledge there is no practical way of assembling an exhaustive and credible list of European ethanol facilities together with their production levels and CO<sub>2</sub> emissions. The three facilities described here are not necessarily representative of other facilities in Europe, and the data described are entirely self-reported.

## **The case of Swedish Biogenic Point Sources from Pulp and Paper, CHP, and Bioethanol Production**

Commencing from the previous sections, we can map the existence of large-scale point sources of biogenic CO<sub>2</sub> emissions in Sweden. For this purpose, we will use data from 2017, available from the Swedish Environmental Protection Agency but yet to be reported to E-PRTR. As a threshold for a facility to be classified as promising for BECCS, we use the following criteria: for the CHP as well as pulp and paper industries, we include facilities reporting biogenic CO<sub>2</sub> emissions of more than 0.5 Mt in 2017, and for ethanol production facilities, we include only the single large-scale (>100 million liters bioethanol per year) production plant in Sweden, i.e., Agroetanol on Händelö in Norrköping. Given these cut-off criteria, 24 industrial facilities were deemed promising for BECCS; of these, 20 were in the paper and pulp industry, three were CHP facilities, and one was an ethanol production facility.

The total aggregate CO<sub>2</sub> emissions from these facilities in 2017 were 24.5 Mt, 23.5 Mt (i.e., 97%) of which were biogenic. In other words, the CO<sub>2</sub> emissions of facilities fulfilling the above cut-off criteria have very high biogenic fractions.

**Figure 4-3 | Large Swedish point sources of biogenic CO<sub>2</sub> emissions from pulp and paper, combined heat and power, and bioethanol production facilities (2017).**



## Summary and Conclusions

European pulp and paper industries emitted more than 70 Mt of CO<sub>2</sub> in 2015, with an estimated average biogenic fraction of 85–95%. A total of 48 facilities emitted more than 0.5 Mt of biogenic CO<sub>2</sub> each. Many of these facilities are geographically clustered in Sweden, Finland, and Portugal, potentially enabling economies of scale.

While the cumulative biogenic CO<sub>2</sub> emissions from the CHP production may be comparable to those from the pulp and paper industry, the number of high-emitting facilities appears to be smaller. Only five CHP facilities explicitly reported high (fflo.5 Mt) biogenic CO<sub>2</sub> emissions in 2015. Three possible

reasons for this are that: (1) production of heat is less centralized than that of paper; (2) fewer CHP facilities have high biogenic CO<sub>2</sub> fractions in their fuel mix; and (3) most CHP facilities are located in countries that do not explicitly report the biogenic fraction of their emissions.

Biogenic CO<sub>2</sub> emissions originating from the production of ethanol are significantly smaller than those from the pulp and paper and CHP industries. The emissions from the fermentation process, which are unusually easy to capture due to their high CO<sub>2</sub> concentration, are estimated to be 4.6–4.9 Mt annually. Anecdotally, a typical large ethanol production facility is likely responsible for 0.2–0.4 Mt of biogenic CO<sub>2</sub> emissions, but there is currently no practical way of establishing an exhaustive list of such facilities and their emissions.

In the case of Sweden, our analysis indicates a potential for BECCS. More than 20 facilities each emitted at least 0.5 Mt of biogenic CO<sub>2</sub> in 2017, and many are located in clusters near the sea. However, many deployment barriers remain, both social and political as well as economic, and technical.

In all three economic activities analyzed here, data quality, availability, and compatibility are insufficient to enable exhaustive and rigorous analysis. There are several reasons for this deficiency, notably:

1. the voluntariness of reporting the fossil share of total CO<sub>2</sub> emissions to E-PRTR limits the possibility of calculating the biogenic fraction;
2. dataset incompatibility between E-PRTR and EUTL, with no identical facility identification keys, limits the possibility of matching registry data based on which the biogenic fraction of total emissions might otherwise have been calculated;
3. activity categories are imprecise and self-reported, and;
4. data are incomplete for activities not covered by the EU ETS, such as waste-to-energy incineration.

In light of these data problems, the calculated BECCS potentials are to be regarded as rough “ballpark” values rather than precise estimates. These figures can be meaningfully compared with, for example, the current global installed BECCS capacity or the predicted levels of BECCS in various climate scenarios.

## Chapter 5

# Governing BECCS: “Slippery Slope” or “Uphill Struggle”?

Rob Bellamy

## Slippery slopes'

Bioenergy with carbon capture and storage (BECCS) and other suggested large-scale interventions in the Earth’s climate system promise new ways of responding to anthropogenic global warming. Complemented by reductions in GHG emissions and adaptations to climate change impacts, these interventions could greatly help reduce global average temperature and the risks associated with its rise. Yet it is more often the imagined undesirable consequences of these interventions that capture the attention of those who would seek to govern them. With respect to BECCS, these are predominantly envisaged as pressures on biosphere integrity, biogeochemical flows, freshwater use, and land-system changes that might result from the large-scale growth of biomass (e.g., Heck et al., 2018).

Such concerns are frequently articulated in the form of “slippery slope” arguments (see Jamieson, 1996; Cairns, 2014): If we do “A” (in this case, BECCS R&D), then this will trigger a chain of events resulting in the objectionable state “B” (here, BECCS deployment and its envisaged undesirable consequences). It would follow then that governance should employ instruments that proscribe or at least constrain BECCS R&D. Underlying the slippery slope argument are two significant assumptions: (1) that research leads to deployment, and (2) that deployment has undesirable consequences. Yet these assumptions are in point of fact both deeply flawed, in turn raising serious doubts about the appropriate-

ness of the dominant proposed approaches to governing BECCS.

Will BECCS research inevitably lead to deployment? Not necessarily. As Steve Rayner has argued, “We know that patent offices are actually the graveyards of dreams. Most patents are death certificates” (Rayner, 2017, p. 121). We need look no further than real-world cases of technological research that never went on to deployment. Despite hundreds of millions of dollars spent on decades of research into fast-breeder nuclear reactors, for example, they have never been deployed. This is not to discount the very real potential for various undesirable (or desirable) path-dependencies (David, 2001) and lock-ins (Arthur, 1989) that can occur during technological R&D. However, these consequences are *not inevitable* and are *not unpreventable* by flexible and corrigible governance architectures for overcoming dilemmas of control (Collingridge, 1980).

In slippery slope arguments, “A” is often “held to be unproblematic or even morally desirable considered on its own” (Jefferson, 2014, p. 674). However, the “the undesirability of the starting point should not enter as a premise in the argument, as the argumentative heft is supposed to come from the undesirability of the consequences,” i.e., “B” (Jefferson, 2014, p. 674). This emphasizes the importance of properly characterizing the endpoint. Will BECCS deployment have undesirable consequences? Not necessarily. First, several strategies for mitigating the possible harmful impacts of large-scale biomass growth are under consideration, such as using carbon-neutral or carbon-negative power, minimizing biomass transport or making it sustainable, or using other biomass processing options (Fajardy & Mac Dowell, 2017). Second, BECCS may develop in a completely different direction altogether and not use land to grow biomass at all, but rather the oceans (Beal et al., 2018). Third, we know from social theory that desirability is selective: people, acting in social groups, emphasize particular risks and deemphasize others to maintain solidarity with their groups (Douglas, 1986).

Slippery slope arguments are routinely criticized for their “frustratingly vague and underspecified” character (Jefferson, 2014, p. 679). Despite their flawed articulation in relation to BECCS and other large-scale climate interventions, their imprint is deeply engrained in the dominant top-down governance

narrative, which pursues the ostensible need to constrain or even proscribe R&D. A survey of governance proposals identifies many that seek to regulate research internationally, including: multilateral control through the UNFCCC (Barrett, 2008; Lin, 2009; Zürn & Schäfer, 2013) or the UNCBD (Bodle, 2014), oversight by new international institutions (Morrow et al., 2009; Zürn & Schäfer, 2013), international codes of conduct (Hubert et al., 2016), other international bureaucratic institutions and advisory bodies (Bodansky, 1996; Humphreys, 2011), as well as more general calls for international agreements (Olsen, 2011). These join the extant *de facto* international moratorium on research agreed to by the UNCBD in 2010.

If this top-down narrative of governing BECCS is even partly based on unsound assumptions about there being a slippery slope from research to undesirable deployment, then this raises serious questions about the appropriateness of the dominant governance narrative itself, and its potential role in undermining R&D that could lead to innovations that help deliver the Paris Agreement targets. Before we can develop appropriate governance, we must first begin to understand the plausible future trajectories of BECCS R&D: If they are not slippery slopes, then what are they?

## Uphill struggles

This section draws on recent research that has begun empirically exploring the question of future trajectories (see Bellamy & Healey, 2018, for full details). Specifically, this research asked how far BECCS might develop in the future and under what governance arrangements. It sought to address this using a novel method of scenario development in which the inputs (e.g., participating perspectives and issues considered) were broadened in response to theoretical imperatives pertaining to highly uncertain and ambiguous topics (see Bellamy et al., 2012; Stirling, 2008). The method consisted of a one-day workshop in London, UK, with 16 international experts and stakeholders in climate change and/or large-scale climate intervention from across government, industry, civil

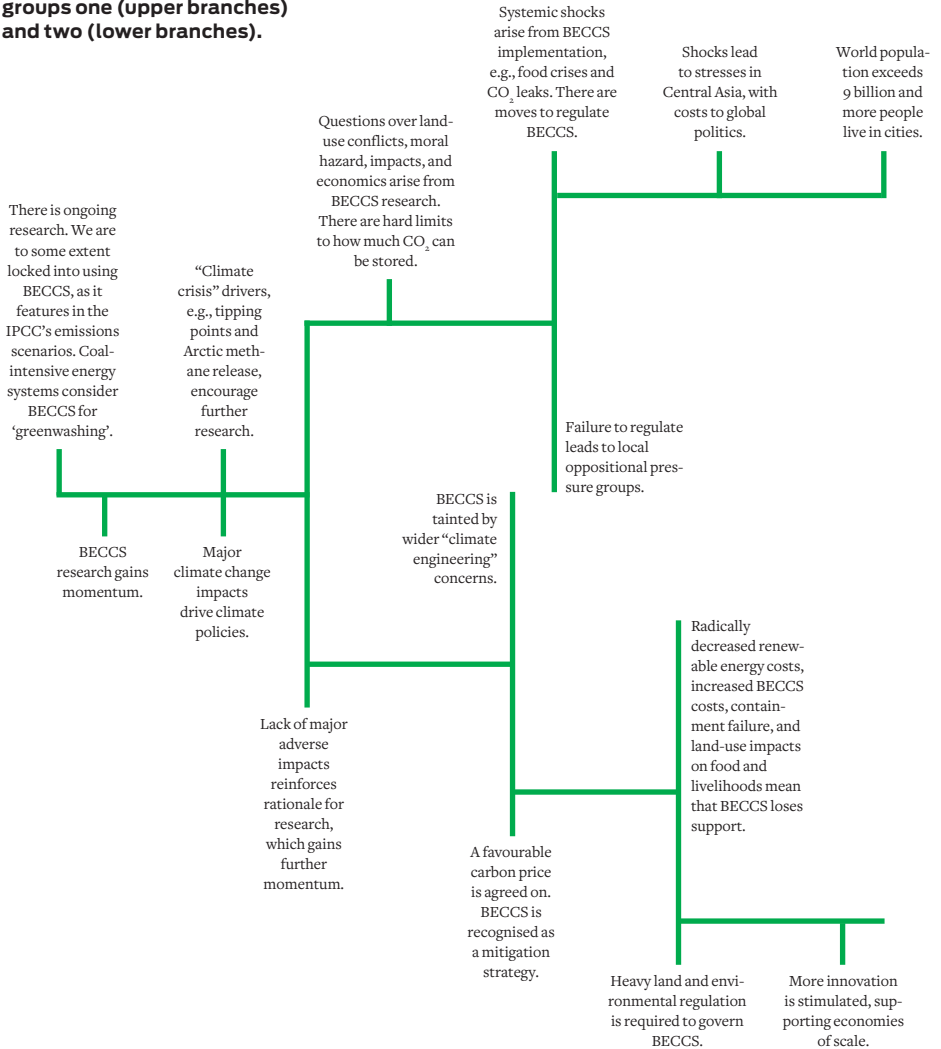
society, and academia, drawn predominantly from the UK, but also including representatives from Brazil, Germany, and India. To explore uncertainties and ambiguities and to generate a richer selection of trajectories, two separate groups developed scenarios for BECCS.

Both groups were asked to consider four idealized approaches to governing BECCS: self-regulation by scientists, engineers, and entrepreneurs; global governance via an international agreement regulating the conduct of research across countries; principles and protocols, i.e., a step-by-step, bottom-up approach; and moratoria proscribing particular activities: if, when, and how each might play a part. The groups then each developed a storyline for BECCS research over the next twenty years, accounting for major events in the development of the technology and its governance. Each group also produced a diagrammatic representation of their scenarios (see Figure 5-1).

Both groups acknowledged that BECCS research was likely to gain momentum in the short term, in no small part due to its prevalence in the IPCC's IAM scenarios. Both groups also saw a pivotal near-term role for the impacts of climate change, such as extreme weather events or large-scale crises (e.g., passing climate tipping points), in stimulating further research. After this, the two groups' scenarios diverged quite markedly, with group one envisaging a pathway characterized by implementation but systemic shocks, and group two envisaging one characterized by a carbon price imperative, definitional politics, and alternatives. In group one, implementation was particularly seen as exacerbating food crises and necessitating strong regulation. A failure to do this was seen as stimulating activist opposition to BECCS. In group two, the imposition of a carbon price and the recognition of BECCS as a mitigation technology were seen as crucial. A failure to recognize BECCS as such was judged to taint the technology by association with other, more controversial large-scale climate interventions. As with group one, regulation was seen as needed once BECCS was deployed. Possible food crises and improvements in alternatives to BECCS, such as other renewable sources of energy, were seen to pose threats.

Broader group deliberations on the scenarios revealed several additional

**Figure 5-1 | Scenarios for BECCS R&D identified by groups one (upper branches) and two (lower branches).**



challenges that might limit how far BECCS would develop. The first of these concerned integration. Group two had begun their discussion by suggesting that BECCS posed a definitional challenge, in that it combined two separate



technologies—bioenergy and carbon capture and storage—that had not yet been fully demonstrated as a single, integrated system. Group one went further and argued that BECCS combined two already unpopular technologies, and that this would make its eventual deployment doubly unlikely. The fact that little political lobbying was taking place for BECCS compounded this perceived unlikelihood. To state this formally, it appears that “A” (i.e., BECCS R&D in its present state) will trigger a chain of events resulting in a vanishingly small likelihood of “B” (i.e., BECCS deployment and its outcomes, whatever they may be).

A second set of challenges facing BECCS was practical in nature. For group one, these challenges concerned the need to ensure a sustainable supply of biomass feedstock. Both the need for and apparent difficulty in securing technical demonstrations of BECCS technology were also raised as challenges, citing the abandoned White Rose project in the UK that would have seen commercial-scale CCS operations installed at the Drax coal-fired and wood pellet biomass power station. Plans for the undersea storage of CO<sub>2</sub> captured at that facility were, however, deemed to have been infeasible. For group two, the practical challenges facing BECCS were more concerned with developing infrastructure at the scales required and ensuring the safety and effectiveness of underground CO<sub>2</sub> storage.

Resource supply was a third challenge of particular importance to group one. Having noted recent significant upward revisions in forecasts of human population by 2100, the possibility of turning land over to biomass production was deemed increasingly unlikely. On the other hand, the use of urban areas for food production and potential dietary changes that could free up land were noted as uncertainties. At this point, the group suggested that biochar production—a candidate large-scale climate intervention in which biomass is pyrolyzed and buried, with claimed benefits to both soil health and agricultural productivity—could be utilized as an alternative to BECCS.

The two groups developed quite different scenarios regarding the governance arrangements under which they envisaged BECCS developing. In line with the principles and protocols approach, group one saw local geopolitical priorities and attendant government investments in R&D as establishing dif-

ferent prospects for BECCS in different places. In Europe, for example, already intensive land use was deemed to make BECCS uptake less likely or prevalent. On the other hand, in China large areas of underused land were deemed to make BECCS uptake more likely or prevalent. China was further noted as being particularly suited to developing BECCS owing to its command-and-control political system and its potential to convert coal-fired power stations to biomass combustion, thereby allowing them to operate longer under growing pressures to decarbonize. Group two instead saw the Paris Agreement as leading to an effective global carbon price. This, they argued, would incentivize BECCS R&D in the private sector by affecting market processes. A failure to create an effective carbon price was seen to leave R&D without significant support from governments and thereby vulnerable to technical failures, changes in energy policy, and regulatory limitations.

## How to govern

Expert scenarios of how far BECCS might develop and under what governance arrangements have revealed manifold technical, political, and societal challenges (summarized in Table 5-1). These findings are consistent with and advance those of expert scenario analyses performed in relation to other large-scale climate interventions. These include several factors thought likely to be significant in influencing the trajectories of R&D, including technical limitations that might arise during the course of R&D and their possible harmful impacts (Banerjee et al., 2013; GAO, 2011; Haraguchi et al., 2015; Low, 2017). Environmental crises in particular are a common feature of such scenarios (Boettcher et al., 2015; GAO, 2011; Low, 2017), highlighted in the present scenarios as both catalysts (e.g., an Arctic methane emergency, climate tipping points, or extreme weather events) and inhibitors (e.g., leaks of captured gas caused by R&D itself or food shocks) of R&D.

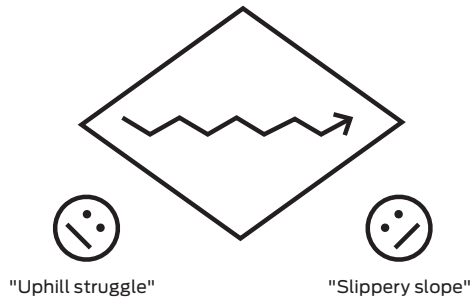
The challenges identified stand in stark contrast to portrayals of R&D as

**Table 5-1 | A summary of envisaged challenges facing BECCS development.**

Technical challenges	Political challenges	Societal challenges
Developing infrastructure at scale	Competition from alternatives	“Climate engineering” taint
Limits to CO <sub>2</sub> sequestration	Environmental regulations	Merger of unpopular technologies
Need for demonstration projects	Geopolitical disparities in uptake	Opposition from activist groups
Safety of CO <sub>2</sub> storage	Need for effective carbon price	Potential for land-use conflicts
Sustainability of biomass supply	Need for government investment	Risks to food production

constituting a slippery slope toward deployment. In point of fact, the scenarios provide empirically grounded accounts of “slippage”—the specific mechanism(s) ordinarily associated with exacerbating the slide down slippery slopes (Lode, 1999)—not toward but *away from* deployment. Indeed, such accounts are notably absent from slippery slope arguments made about BECCS and other large-scale climate interventions. In these ways, BECCS progress bears much less resemblance to a slippery slope than to what might best be described as an “uphill struggle.” To state this formally, it appears that starting “A” (i.e., BECCS R&D) will trigger a chain of events resulting in a vanishingly small likelihood of “B” (i.e., BECCS deployment and its outcomes, whatever they may be).

The fact that expert scenarios project futures for BECCS R&D characterized by uphill struggles does not mean that there is no risk of there being a slippery slope. Although BECCS can be deemed to have a higher level of technological readiness than many other prospective large-scale climate interventions, it remains manifestly “upstream” of significant R&D. This means that our knowledge of what might happen and of the probabilities of these things happening is necessarily incomplete (Stirling, 2007). This creates a state of incertitude in which conflicting judgments about the outcomes of BECCS R&D may be made (simplified in Figure 5-2). While slippery slope arguments have hitherto been flawed and scenarios that have been broadened to encompass diverse viewpoints did not find any slippery slopes, this is not to say that we can entirely discount the possibility of their existence. The problem, as already seen, is that

**Figure 5-2 | Framing research into deployment: slippery slope or uphill struggle?**

slippery slope thinking has helped create and sustain a dominant top-down governance narrative that seeks to constrain or proscribe BECCS R&D.

The combination of exposed flaws in slippery slope argumentation and emerging accounts of an uphill struggle suggest that a significant shift is needed in how we think about the governance of BECCS. Rather than seeking to constrain or proscribe R&D, governance should be seeking to *incentivize* it. Yet just as it is problematic to adopt the partial slippery slope viewpoint and seek to constrain or proscribe BECCS R&D without knowing more about its outcomes, so too would it be problematic to adopt a partial uphill struggle viewpoint and seek to incentivize such R&D without accounting for societal values and concerns (see Table 5-2). R&D must therefore be incentivized *responsibly* to allow BECCS to progress to a point of sociotechnical maturity that enables informed and robust decision making about whether it should be deployed and, if so, under what conditions. There needs to be broad societal participation in defining the tools and terms of that incentivization (Bellamy, 2018).

The much-needed shift toward responsible incentivization necessitates a move away from the dominant top-down international approaches to governing BECCS toward bottom-up national ones. Indeed, the Paris Agreement itself—with its bottom-up architecture structured around nationally determined contributions—makes this essential. Such an approach would enable the development of a variable geometry whereby the incentivization of BECCS or indeed any other option for tackling climate change can be considered in terms

**Table 5-2 | Governance implications of different research and development framings.**

R&D framing	← Slippery slope			Uphill struggle →	
<b>Governance implications</b>	Proscribe	Constrain	Responsibly incentivize	Incentivize	Prescribe
<b>Example proposals</b>	(Inter)national moratoria	(Inter)national regulations	Participation in definition	Remunerative instruments	Coercive instruments

of local portfolios determined by local values and interests. These different portfolios might then form “geopolitical stabilization wedges” as distinct from the sorts of contextually neglectful, technology-fixated wedges featured in the literature to date (Bellamy & Healey, 2018; cf. Pascala & Socolow, 2004).

## Conclusions

Concerns around BECCS are frequently articulated in the form of “slippery slope” arguments, contending that research will necessarily lead to deployment and that deployment will be undesirable. This chapter has critically examined this argument and reported on an expert scenario analysis designed to explore how far BECCS might develop in the future and under what governance arrangements. From this combination of critical and empirical analyses, we can draw three main conclusions:

1. *Slippery slope arguments about BECCS are flawed in at least two fundamental ways.* First, we know from real-world cases of technological research that never went on to deployment that BECCS research will not inevitably lead to deployment. Second, we know from proposed strategies for mitigating the possible harmful impacts of large-scale biomass growth, from alternative, ocean-based directions for R&D, and from an understanding that desirability is not universal but depends on social context, that deployment may not be undesirable. This undermines the dominant top-down governance narrative that slippery slope thinking has helped to create and sustain, and that seeks

to constrain or proscribe BECCS R&D.

2. *Expert scenarios suggest that future BECCS R&D resembles more of an “uphill struggle.”* Manifold technical, political, and societal challenges contrast starkly with portrayals of R&D as constituting a slippery slope toward deployment. Scaling infrastructure, ensuring sustainable biomass, competition from alternatives, the need for investment, the “climate engineering” taint, and the potential for land-use conflicts are some of the challenges that provide an account of “slippage” that is missing from slippery slope argumentation. This further undermines slippery slope-inspired calls to constrain or proscribe R&D.
3. *Approaches to governing BECCS need to shift toward responsible incentivization.* While slippery slope arguments are flawed and expert scenarios do not find a slippery slope but rather an uphill struggle, we cannot entirely discount their possibility. To account for societal concerns there needs to be broad participation in defining the tools and terms of a governance shift in the direction of incentivization, so that BECCS can progress to a point of sociotechnical maturity that enables informed and robust decision making about whether the technology should be deployed and, if so, under what conditions.

This chapter has proposed a fundamental shift in how we think about the governance of BECCS. This turn to responsible incentivization is important for two key reasons. If we proceed under the top–down international approaches to constraining or proscribing R&D that dominate current thinking on governance, then we may lose a potentially very significant contributor to geopolitical wedges for climate stabilization. On the other hand, if we ignore societal concerns when incentivizing BECCS R&D, we risk making ineffective, contested, and technocratic decisions about our future.

## Chapter 6

# Multilevel Policy Incentives for BECCS in Sweden

Mathias Fridahl and Rob Bellamy

**Many have noted** a lack of policy incentives for BECCS, from R&D to commercialization. That BECCS is unlikely to materialize without incentivization policy has been alluded to throughout this book. For example, the climate scenarios' high level of BECCS deployment, discussed in chapter 2, is as much the result of assumed cost curves as of assumptions related to a continuously increasing carbon price. Real-world deployment, however, is currently close to nonexistent. At present, only a few pilot or demonstration projects exist.

How might incentive structures be envisioned? Are existing climate policies likely to incentivize any BECCS development? Here, we explore such questions by mapping existing policy incentives for BECCS research, development, demonstration, and diffusion (RDD&D). We do so by looking at a climate policy frontrunner with exceptionally favorable potential for BECCS deployment: Sweden.

As discussed in chapter 4, the large Swedish bioeconomy includes substantial point sources of biogenic CO<sub>2</sub> in multiple sectors. Biogenic CO<sub>2</sub> emissions are large in the widespread Swedish pulp and paper industry, in the production of electricity and heat, including through waste incineration, and in bioethanol production. This, in combination with the Swedish climate policy framework targeting net-zero emissions by 2045 and carbon-negative emissions thereafter, makes Sweden interesting as a potential early adopter of capturing biogenic emissions of CO<sub>2</sub>.

Policy, however, is often developed at multiple levels. Understanding how

existing policy is or is not able to incentivize BECCS RDD&D therefore requires a multilevel analysis. Here, we focus on climate policy instruments directly relevant to BECCS RDD&D at three levels: the UN, the EU, and in Sweden.<sup>3</sup> Policy instruments are “the techniques or means through which states attempt to attain their goals” (Howlett, 2011, p. 22), i.e., tools for achieving policy objectives. Analytically, policy instruments can be divided into three types (Bemelmans-Videc et al., 2010):

1. “Carrots,” or economic instruments, act to incentivize measures in line with political goals; examples are taxation, subsidies and R&D grants, and emissions trading.
2. “Sticks,” or regulatory instruments, are binding rules, such as direct controls or mandatory equipment.
3. “Sermons,” or informational instruments, are attempts to influence action through the transfer of knowledge and persuasion; examples are public information campaigns and appeals to corporate social responsibility.

We use this typology to classify UN, EU, and Swedish climate policy instruments directly relevant to BECCS. The instruments are further evaluated in terms of their targeted steps in a) the BECCS value chain and b) the technology RDD&D phases. For readability, we concentrate on the main instruments of significance to BECCS RDD&D, excluding several instruments expected to have minor influence.

This exercise results in a map of how various types of climate policy instruments at different scales do or do not provide incentives directly relevant to BECCS. While the mapping exercise is admittedly stylized—in practice, a BECCS R&D fund, for example, is directly relevant to R&D yet could indirectly incentivize deployment through covering part of the cost of moving a technology from being an uncompetitive idea researched for optimization to commercial products—it provides an overview of importance for evaluating existing and planning for alternative policy mixes.

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<sup>3</sup> UN, EU, and Swedish policy instruments were retrieved from the following online repositories for laws and guidelines: UNFCCC, [www.unfccc.int/documentation/document\\_lists/items/2960.php](http://www.unfccc.int/documentation/document_lists/items/2960.php); IMO, <https://docs.imo.org>; IPCC, [www.ipcc.ch/publications\\_and\\_data/publications\\_and\\_data.shtml](http://www.ipcc.ch/publications_and_data/publications_and_data.shtml); the EU, [www.eur-lex.europa.eu](http://www.eur-lex.europa.eu); and Sweden, [www.riksdagen.se/en/documents-and-laws](http://www.riksdagen.se/en/documents-and-laws).



## Existing policy drivers and barriers to BECCS RDD&D

### The UN

Sweden has ratified several international agreements relevant to BECCS. Of these, treaties and decisions under the auspices of the UN Framework Convention on Climate Change (UNFCCC) are intuitively among the more important. However, the Intergovernmental Panel on Climate Change (IPCC) and the International Maritime Organization (IMO) have significant influence too. Here, the most relevant instruments and how they might influence BECCS RDD&D in Sweden are discussed.

While the UNFCCC provides goals and establishes principles, its Kyoto Protocol focuses more on policy instruments, including economic instruments to increase the cost effectiveness of meeting the emission reduction commitments of Parties to the Kyoto Protocol.

The Clean Development Mechanism (CDM), an instrument of tradable emission credits, can be used by developed countries to invest in mitigation activities in developing countries. Proven emission reductions, relative to a baseline, generate tradable emission credits that can be used for compliance. In 2011, the UNFCCC decided to include carbon capture and storage (CCS) in the CDM. However, the mechanism does not provide direct support to BECCS in Sweden. Furthermore, no methodology for a CCS CDM project has yet been approved. This is unlikely to occur, because the market for CDM credits has collapsed with declining interest in the Kyoto Protocol and the EU's restriction on linking CDM credits to the EU Emissions Trading System (EU ETS). In addition, the approval requirements for CCS methodologies are unusually strict (Dixon et al., 2013, p. 7598). Other instruments act similarly, including the Joint Implementation Mechanism and emissions trading. However, these too are unlikely to spur BECCS deployment in Sweden for reasons similar to those for the CDM.

Emissions trading operates under a different logic, allowing Kyoto Protocol Parties to sell surplus emission reductions in the event of overcompliance. In

practice, however, a large aggregated surplus was generated from the collapse of former Soviet bloc industry. Some assessments even suggest that a few countries complied with commitments in the 2008–2012 period simply through buying surplus reductions from Poland, Romania, and the Czech Republic, which were cheaper than domestic mitigation actions (Martínez de Alegría et al., 2017; Shishlov et al., 2016). This undermines incentives for states to invest in expensive BECCS for the purpose of generating surpluses to be sold to others for their compliance. The second commitment period of the Kyoto Protocol, 2013–2020, involves far fewer Parties, most of which have already designed a system for emissions trading based on the Kyoto Protocol's provisions.

The Kyoto Protocol's mechanisms are, arguably, losing traction, not least since the Protocol lacks emission reduction commitments beyond 2020. More recently, new market-based mechanisms have been in development under the Paris Agreement, which in all likelihood are influenced by the Kyoto Protocol's mechanisms. One example is a new mechanism to promote mitigation and support sustainable development (Article 6.4) that is likely to start operating in a fashion similar to that of the CDM by 2020. To what extent this mechanism will attract funding and maintain liquidity at carbon prices that will drive investments in BECCS in Sweden remains to be seen.

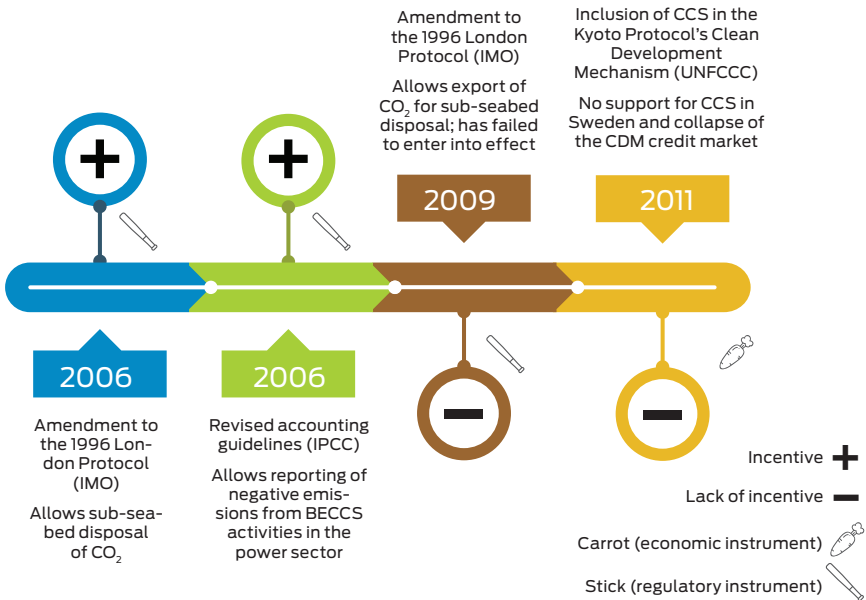
The UN, through the IMO, has also regulated prohibitions related to the sub-seabed disposal of CO<sub>2</sub>.

Since 2006, the London Protocol to the IMO Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter has been amended to allow sub-seabed disposal of CO<sub>2</sub> within countries. However, Article 6 of the same protocol still prohibits exporting CO<sub>2</sub> for sub-seabed disposal in another country. In 2009, the Protocol was amended to allow such exporting, though the amendment has not entered into force due to lack of ratifications. Exporting is therefore still prohibited among contracting parties (Dixon et al., 2014). One of the most discussed scenarios for BECCS in Sweden involves exporting to sub-seabed storage sites in Norway. At present, such exporting would breach international law, which creates uncertainty among potential private investors.

The international community has also designed accounting guidelines to

measure compliance with international commitments. The UNFCCC links national accounting to IPCC methodologies that, since 2006, have allowed states to consider negative emissions resulting from BECCS in accounting for compliance with commitments. States are therefore provided incentives to pursue BECCS, yet the extent to which they can transfer such incentives to businesses and public utilities is pending, awaiting conducive supranational and domestic policy.

**Figure 6-1 | The most significant UN climate policy instruments relevant to BECCS.**



## The EU

EU climate objectives are to be achieved mainly through two instruments: the EU Emissions Trading System (EU ETS) and the Effort Sharing Decision (ESD) regulating actions in sectors not covered by the EU ETS. In addition, there are economic policy instruments designed to subsidize investments.

The EU ETS is an instrument governing tradable emission rights. The system is based on allowances and currently does not allow the generation of new allowances based on negative emissions. If negative emissions were to generate

allowances that could be sold in the system, they ought to be complemented with measures to cancel allowances in other parts of the system. Such a reform would require amendments to existing rules, for example by an automatic lowering of the system's cap corresponding to each allowance generated through negative emissions. Including BECCS within the EU ETS would also require amendments to the general EU ETS rule of excluding biogenic emissions (and sinks).

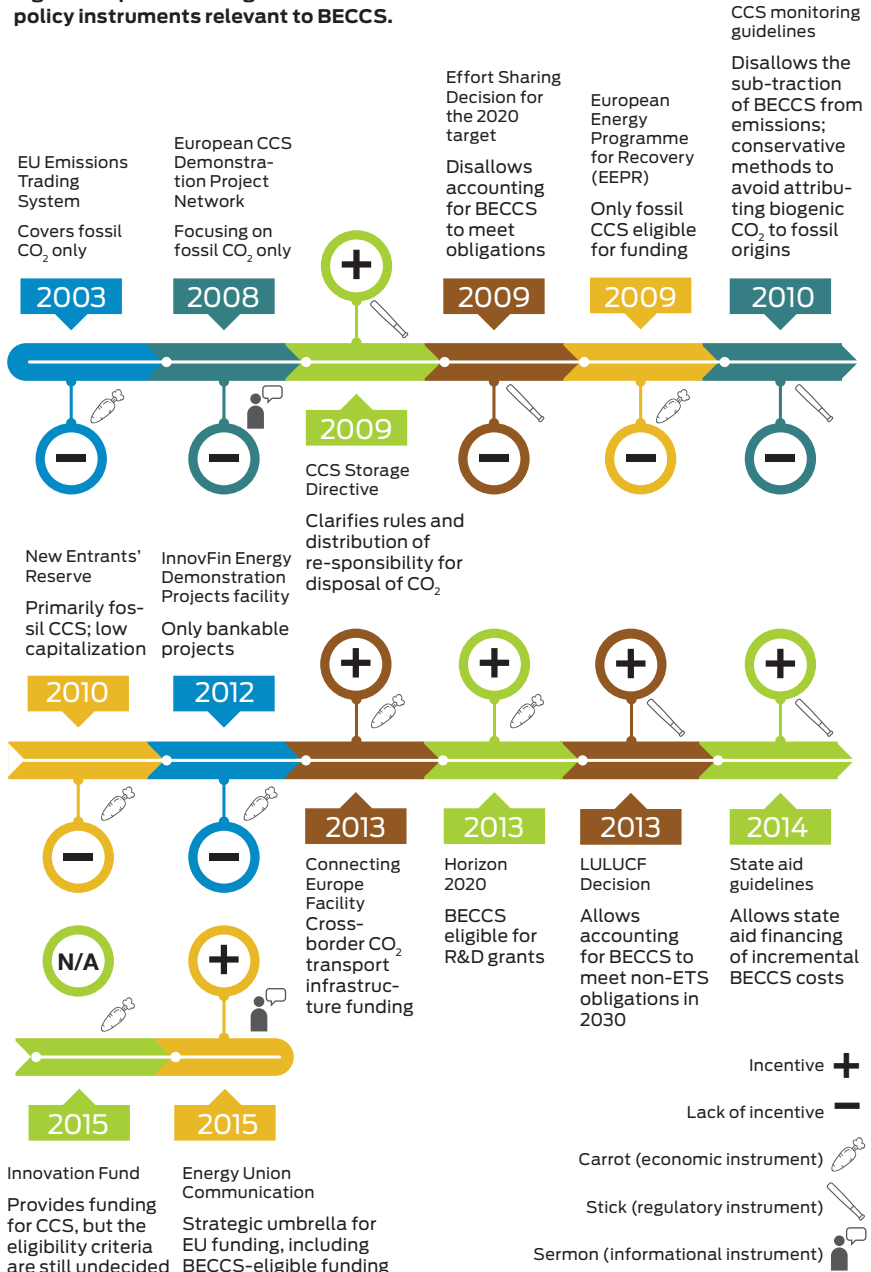
The EU ETS has also been accused of failure to drive innovation, for example, of fossil CCS (Åhman et al., 2018). This problem is acknowledged by the EU, which has agreed on a number of R&D subsidies to complement the EU ETS.

While many of these funding sources target CCS, they limit funding to fossil energy. BECCS is eligible for funding from some of these sources, such as Horizon 2020 and the Connecting Europe Facility (for CO<sub>2</sub> transport). However, this funding is provided in isolation from policies that create market pull for negative emissions. The lack of a market covering operational expenditures makes investments in BECCS unprofitable and risky, even if the incremental costs of capital expenditure are supported through investment funds (Åhman et al., 2018).

In this context, with EU's economic climate policy instruments mostly failing to incentivize BECCS, several EU regulatory instruments are more favorable. The CCS Directive, for example, strengthens the legal certainty for CCS in Europe, most notably including rules related to the geological storage of CO<sub>2</sub>. At the same time, as with the economic instruments, the CCS Directive does not induce market pull for negative emissions (Duscha & del Río, 2017).

In addition, since 2018, an EU regulation has linked land use, land-use change, and forestry (LULUCF) to the EU 2030 target for emissions not covered by the EU ETS. The LULUCF regulation requires that all LULUCF and agriculture emissions, in each member state, must be balanced by removals. The regulation is also linked to the ESD; if net emissions from LULUCF are positive, a member state may use a limited number of surplus emission allocations from the ESD to offset LULUCF emissions and thereby complying with the LULUCF "no debit" rule. On the other hand, if a member state has surplus removals resulting

**Figure 6-2 | The most significant EU climate policy instruments relevant to BECCS.**



CCS monitoring guidelines  
Disallows the sub-traction of BECCS from emissions; conservative methods to avoid attributing biogenic CO<sub>2</sub> to fossil origins

from afforestation or managed grass- or cropland, these may be used for ESD compliance. The regulation also allows EU countries to trade surplus removals between member states.. Overall, the regulation provides incentives for states to ensure the carbon-neutral production of biomass and allows accounting for negative emissions from BECCS. Yet such negative emissions, even if accounted for, do not create assets for firms or municipal utilities.

## Sweden

The carbon tax, introduced in 1991, is one of the best-known Swedish climate policy instruments. The tax, pricing carbon above EU 120 per tonne CO<sub>2</sub> in 2018, has been a substantial factor driving the expansion of the Swedish bioeconomy (Börjesson et al., 2017). At this price level, BECCS would be incentivized. However, the law does not put a tax on biogenic CO<sub>2</sub> emissions. Furthermore, as a tax instrument, it only rewards emission reductions down to zero; negative emissions are not rewarded. The tax has arguably driven the expansion of the bioeconomy in general, for example, by increasing the share of bioenergy in the production of electricity and heat (Börjesson et al., 2017). However, it does not provide a direct incentive for BECCS.

A second well-known instrument is the law on renewable electricity certificates, established in 2003. The system issues certificates to producers of renewable energy. It also requires that electricity suppliers and some end users hold certificates corresponding to a particular proportion of their electricity sales or use. In 2016, certificates were granted for 1967 GWh from biofuel and peat, corresponding to about 17% of all certificates for that year. However, while the system, much like the carbon tax, may reward the expansion of biomass-based electricity, it does not reward negative emissions as such.

In 2017, the government published a decree that launched the Industrial Leap Fund, a pledge to provide EUR 31 million annually from 2018 to 2040 for the reduction of process-related industrial emissions. The decree was motivated by the high process-related emissions and equally high costs and investment risks for achieving technological breakthroughs to mitigate these emissions. For example, biorefineries, a sector with BECCS potential, are eligible

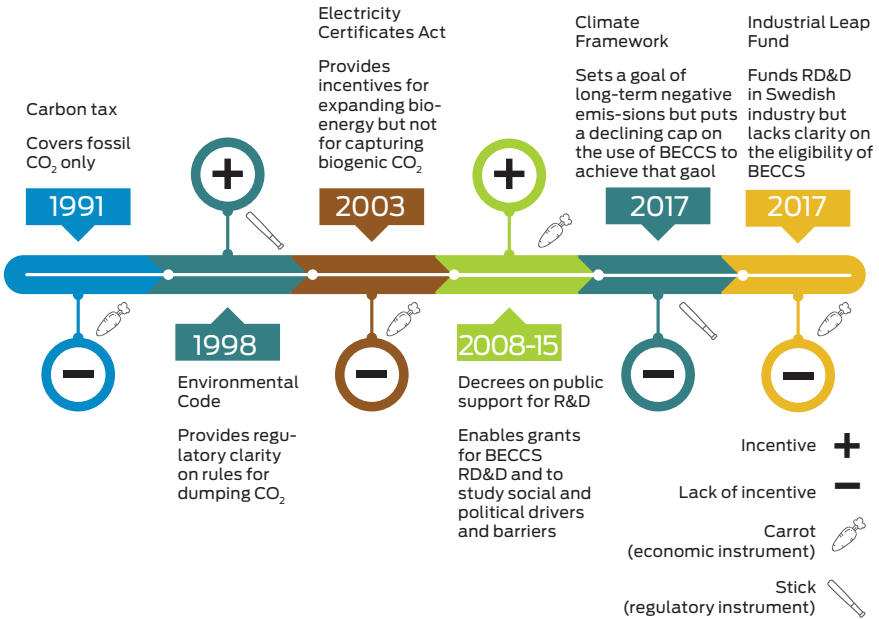
for funding. Whether the pulp and paper industry can apply for BECCS funding, however, remains unresolved. Bioenergy could also replace fossil energy in steel and cement production, sectors eligible for funding and that have partial potential for BECCS. The Fund is thus somewhat promising when it comes to incentivizing BECCS R&D. However, it remains unclear whether pulp and paper, electricity, and heat, sectors with high potential for BECCS, are eligible for funding. Furthermore, long-term funding is not secured upfront. In its current form, only EUR 31 million of the total EUR .72 billion pledge for 2018–2040 was secured in the 2018 budget, and future governments are not obliged to continue supporting the Fund. In addition, several R&D funds are governed through decrees issued in 2008–2015, designed to support technical and policy development, capacity building, and the exploration of social preconditions for deployment. As such, they build capacity both to understand the preconditions for BECCS in Sweden and to develop hardware.

In terms of “sticks,” the long-term goal of net-zero emissions by 2045 is complemented by mid-term goals for emission reductions in non-ETS sectors of at least 63% by 2030 and 75% by 2040, relative to 1990 levels. LULUCF is explicitly not included. As such, even if Sweden is allowed to account for a LULUCF sink in compliance with its ESD commitment, the sink cannot be used to meet the domestic target. However, the intermediate targets may be met using so-called complementary actions up to a maximum of eight (2030) and two (2040) percentage points. Such actions include BECCS, international offsetting, and net LULUCF uptake. This means that if no other complementary actions are used, accounting for BECCS to meet the targets is limited to 2.6 Mt CO<sub>2</sub> in 2030 and 0.7 Mt CO<sub>2</sub> in 2040. The share of allowed BECCS is therefore both limited and declining in the medium term (i.e., from 2030 to 2040), though the framework also specifies that the share will likely have to increase in the long term, beyond 2045. The message conveyed by regulators on the future role of BECCS in Swedish climate actions is therefore somewhat mixed.

The regulation of storage infrastructure is more conducive. In Sweden, geological storage potential is mostly found offshore, in the Baltic Sea. The existing policy mix consists of four main regulatory instruments: the Directive

on Geological Storage of CO<sub>2</sub>, the Continental Shelf Act, the Certain Pipelines Act, and the Environmental Code. Combined, they provide clarity on rules and responsibilities related to prospecting, building, and operating transport and storage facilities. This increases the predictability of the market conditions for BECCS. However, this also, for good reasons, puts a relatively high administrative burden on actors wanting to open new storage facilities above 0.1 Mt CO<sub>2</sub> in capacity and creates investment risks related to the juridical interpretation of the law, which has proven more blurred than the law itself (Stigson et al., 2016).

**Figure 6-3 | The most significant Swedish climate policy instruments relevant to BECCS.**



## Conclusions

Even though BECCS is considered a key mitigation technology in most 2.0–1.5°C-compatible climate scenarios, there is a significant gap between its technical and market potentials. As shown here for the case of Sweden, existing climate policy instruments are unlikely to achieve this incentivization, at least



beyond R&D. Most relevant instruments at all scales—from the UN, through the EU, to the domestic Swedish policy levels—are economic, yet they mostly fail to act as incentives, threatening to impede rather than encourage BECCS RDD&D.

The pattern of regulatory instruments is more positive, with a slight emphasis on incentivization across all scales. However, this incentivization is undermined by the high transaction costs related to administering carbon storage. The coercive “sticks” are currently the predominant driver of BECCS RDD&D, whereas the remunerative “carrots” in fact fail to provide incentives at all scales. These regulatory and economic instruments are also contradictory and actively counteract each other. For example, the EU CCS Directive as well as the Connecting Europe Facility are designed to facilitate the cross-border transportation of CO<sub>2</sub>, while the IMO’s London Protocol prohibits the same if the purpose is sub-seabed storage. We also find very few informational instruments at all scales. The scope for harmonizing existing climate policies across scales is therefore large.

While some RD&D funding is available through existing instruments, instruments that create market pull enabling revenues from negative emissions to cover operational costs—crucial to deployment—are largely lacking. This elevates the “uphill struggle” facing BECCS RDD&D, as discussed in chapter 5. To ease this struggle, it would be advisable both to remove disincentives and develop new incentivizing policy instruments, with economic incentives through subsidies being the most obvious place to start. For example, governments could guarantee a higher price for producers of electricity and heat implementing BECCS, or could pay a fixed amount to BECCS operators based on levels of carbon removal. Overcoming the dearth of informational instruments at all scales is another area ripe for development, with possibilities to design instruments that help develop premium market segments.

## Chapter 7

# Spearheading negative emissions in Stockholm's multi-energy system

Kåre Gustafsson

**When emissions of GHGs** are closing in on zero in a certain system or geography, is it then time to lean back and be satisfied? Or should we strive for ever-improving climate performance in every system? The current situation, with the achievability of the Paris targets in question, implies that no system, or even human being, with potential for improvement can afford to stand still.

The Stockholm multi-energy system provides electricity, district heating, district cooling, and energy recovery from waste with comparatively small GHG emissions. However, to meet the Paris targets, there is a need to follow a trajectory toward negative emissions. Below-zero emissions are required globally in the second half of the century (Fuss et al., 2018).

Stockholm Exergi AB is jointly and in equal shares owned by the City of Stockholm and the Fortum Corporation.

### Key figures 2017

Annual turnover:	6 638	MSEK
Employees:	707	FTE
Heat delivered:	8.2	GWh
Electricity delivered:	1.6	GWh
Cooling delivered:	0.3	GWh

Energy suppliers and users currently close to zero emissions could be the first explorers of the realm of negative emissions, while others will have to concentrate on the urgent task of mitigation, which is the prime strategy for achieving the Paris targets (UNFCCC, 2015). Besides, the time factor is important (Greg-

ory et al., 2018), and energy users with high emissions will take longer to achieve negative emissions. In that sense, the multi-energy system in Stockholm should be considered a forerunner.

To attain negative emissions, many preconditions and circumstances need to be in place (as discussed by Honegger & Reiner, 2018, and Linde, 2017), not least policy instruments, as described in chapter 6.

## From Paris to Sweden

The Paris Agreement is to be implemented through joint cooperation among all its contracting parties (i.e., states), which are responsible for their territorial emissions.

In line with the need for negative emissions, the Swedish parliament adopted a climate policy framework in June 2017. The framework comprises three parts: long-term climate goals, a planning and monitoring system, and a climate policy council. Parts of the framework are regulated by the Climate Act.

The framework dictates that Sweden is to have net-zero emissions by 2045. This is primarily to be achieved by reducing emissions by at least 85% compared to 1990 levels. Residual emissions are to be offset by complementary measures, such as negative emissions. Bioenergy with carbon capture and storage (BECCS) is specifically mentioned as one possible negative-emission technology (NET). After 2045, Sweden is intended to have net-negative emissions.

Achieving net-zero emissions in 2045 without complementary measures is unlikely, though. For example, net-zero emissions will require all transportation be completely free of CO<sub>2</sub> emissions. All private cars, heavy vehicles, trains, aircraft, and ships will need to be supplied with zero-emission fuels or energy. Of Sweden's approximately 4.8 million cars (SCB, 2018), 600,000 are more than 18 years old. This means that for all cars in Sweden to be zero-emission cars by 2045, no fossil-fuel cars should be on the market by the mid 2020s. In 2017, the number of potentially emission-free vehicles in Sweden was around 275,000. This rough calculation conveys the urgency and need for radical change, as well as the

infeasibility of a trajectory relying solely on conventional abatement.

Another segment is electric power production, which must be based solely on completely fossil fuel free resources, such as hydro, wind, and solar energy. Nuclear energy and sustainable biomass are also options, if their fuel supply is produced and transported using emission-free machines and vehicles.

Other sectors with transformative needs are the steel and concrete industries, whose emissions are not fuel dependent, but stem from the production process itself. For steel production, the option on the table in Sweden is called the HYBRIT project, in which fossil coal is to be replaced with hydrogen (HYBRIT, 2018). For concrete production, carbon capture and storage (CCS) is one of few alternatives to reduce emissions to zero (Bataille et al., 2018).

A further challenge is plastics. No fossil plastics can be disposed of through incineration if zero emissions are to be achieved: either a recycling rate of 100% or a transition to 100% bioplastics is needed. It has been found that the current recycling rate for plastics in household waste in Stockholm is below 7% (Solis, 2018), with no clear path toward recycling rates close to 100%. The current amount of bioplastics as a proportion of all plastics used is 1% globally.

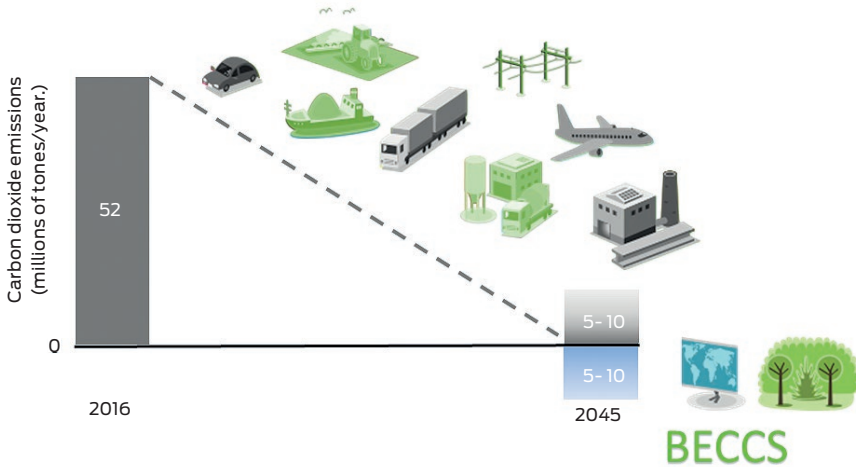
These are just a handful of the hurdles that need to be passed to achieve zero emissions of GHGs. Is this likely to happen, even with stringent legislation and policies? Realistically, the answer is no, and the inevitable conclusion is that negative emissions are needed, a line of reasoning proposed by Geden, Scott, and Palmer (2018). It should be kept in mind, however, that NETs should not be allowed to distract from the urgent task of reducing emissions (Anderson, 2015).

The Swedish climate policy framework also follows this logic, calling for any residual emissions in Sweden by 2045 to be reduced by complementary measures such as NETs. The complementary measures mentioned are:

- increased net uptake of carbon in forest and land
- verifiable emission reductions through investments in other countries
- separation and storage of biogenic CO<sub>2</sub> (i.e., BECCS)

The underlying idea of the Swedish climate policy framework is illustrated in Figure 7-1.

**Figure 7-1 | Schematic of the Swedish climate framework. The goal in 2045 is net-zero emissions of GHGs; residual fossil CO<sub>2</sub> emissions can be offset by negative emissions.**



Despite advantageous conditions (to be discussed later), implementing BECCS could be time consuming. Investments of a similar magnitude have taken 5–15 years to realize in the Stockholm multi-energy system, encompassing all steps from idea to realization. A large-scale BECCS unit, removing 800,000 tonnes of CO<sub>2</sub> yearly, will need at least the same amount of time, assuming that the relevant policies are implemented now. If not, the timeframe would extend further.

It can be concluded that Sweden is highly likely to need complementary measures, such as BECCS, to achieve its national climate goals. This is even more likely after 2045, when Sweden is to have net-negative emissions. As development times could be long, it is essential to act without further delay.

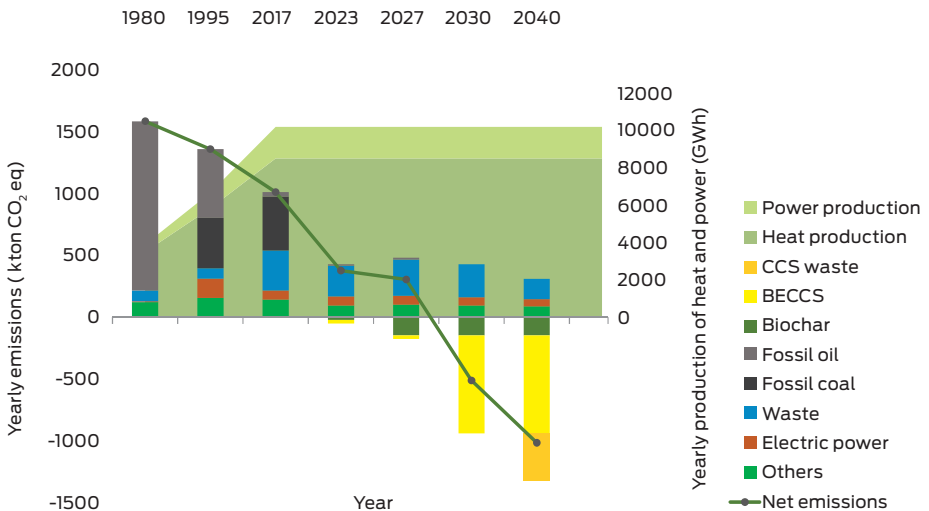
## Achieving negative emissions through a multi-energy system

To achieve its climate targets, Sweden needs transformative changes; incremental changes are not enough (Mistra Carbon Exit, 2018). It can be debated whether it is transformative to turn the Stockholm multi-energy system from

emitter to demitter. It might be more of a transition, achieved over time by incremental steps. Nevertheless, the sheer number of steps could amount to breaking the zero emission barrier. Consequently, from a mitigation point of view, such a change should not be disregarded. Especially since the system can be said to provide a completely new service in the form of negative emissions, which certainly is transformative.

One possible pathway taking Stockholm's multi-energy system from its historical emissions of 1980 to a future scenario of net-negative emissions is shown in Figure 7-2.

**Figure 7-2 | One possible pathway from historical GHG emissions in 1980 to a future scenario of net-negative emissions in the Stockholm multi-energy system.**



## The district heating system in Stockholm

The backbone of the multi-energy system in Stockholm is the district heating system. It consists of a network of pipes that supply buildings with heat produced in centralized plants. Hot water is pumped from the plants and is returned at a lower temperature from the heat consumers. In Stockholm, the heat is transferred through heat exchangers to radiator systems in the supplied buildings.

In Sweden, the concept of district heating was introduced in 1948 in the town

**Figure 7-3 | Schematic of a district heating system. Hot water is distributed from centralized production units and returned at a lower temperature.**

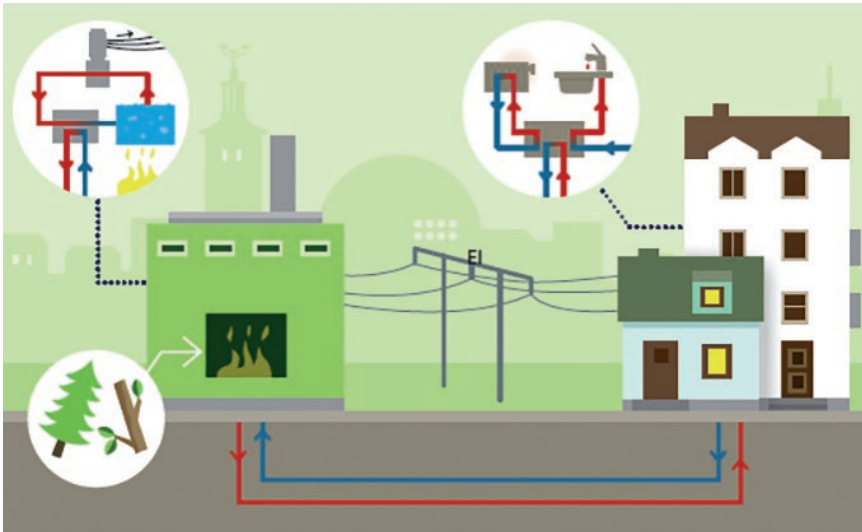


Illustration: Stockholm Exergi.

of Karlstad. In the following decades, systems went into operation in other cities. By 2005, the market share of district heating in residential and service-sector buildings was around 50% (Werner, 2017). Multifamily households are the dominant customers, though single-family houses are connected quite extensively in some cities.

The system in Stockholm has evolved into one of the most advanced multi-energy systems in the world. A thorough description of the system and its dynamics is presented by Levihn (2017).

The evolution began with smaller isolated districts having their own piping networks and heat production. These districts were gradually connected into larger clusters of plants and pipe networks. The first plant to supply heat and electricity simultaneously was the Hässelbyverket Combined Heat and Power (CHP) plant which was commissioned in 1959.

**Figure 7-4 | The Stockholm district heating network is one of the most advanced in the world. There are five major sites where heat is produced. The satellite production units are not shown on the illustration.**



Illustration: Stockholm Exergi.

Increased connectivity between smaller systems has several advantages. When one plant is unavailable another can be started to replace it. In addition, the most efficient plants using cheaper fuels can be operated first to lower the overall production cost. There is also the option of running the most sustainable plants first to lower emissions.

In addition, large systems permit large investments to be made, for example, in CHP plants that can be operated efficiently year round, producing substantial amounts of electricity, rather than in relatively simple heat-only boilers.

The Stockholm Exergi district heating system	Heat production (max):	4.8 GW
	Heat produced:	8 TWh
	Heat produced (incl. partners):	12 TWh
	Length of pipes:	2 900 km

Nowadays, the Stockholm Exergi system is connected with several other utilities, and the total system provides the Stockholm region with 12 TWh of heat every year.



## History: Transformation from high to low carbon

The early clustering of districts into a larger system was described above. The year 1980 marked the addition of the first non-fossil production to the Stockholm district heating system, when the waste-incineration boilers in the southern suburb of Högdalen came online. Earlier heat production was solely based on fossil oil and some coal. The GHG sources in 1980 were as follows:

- fossil oil
- the fossil-origin part of incinerated waste
- the production and transportation of fossil fuels
- the production and transportation of consumables
- dinitrogen oxide and methane

In the following decade, the electricity price was low due to high levels of hydro and nuclear power generation in Sweden, triggering the introduction of electric boilers and large-scale heat pumps (Di Lucia & Ericsson, 2014). These investments were highly profitable with a payback time of only a few years. The emissions focus in 1980s Sweden was largely sulfur dioxide and nitrogen dioxide (Werner, 2017). In response, the company ABB Carbon developed a “clean” coal technology, the so called pressurized fluidized bed combustion (PFBC), for the low-emission production of electricity and heat. The City of Stockholm decided to invest in a PFBC plant in the late 1980s, and it is still in operation today.

In the 1990s, the next development phase began as fossil oil was gradually replaced with biomass and bio-oil. Three oil-fired boilers (80 MW each) were converted to burn wood pellets, and several other boilers were converted to burn bio-oil, mainly tall pitch oil. Investments were made in new boilers for waste and wood chip combustion at the end of the decade. The overall result was that while the total demand in the system increased, its CO<sub>2</sub> emissions decreased.

In parallel, various smaller efficiency initiatives were taken, such as increased energy recovery from flue gases through use of economizers and flue gas condensers, more efficient detection of refrigerant leaks, and the speed control of pumps lowering electrical consumption.

The trend that had begun in the 1990s escalated in the new millennium: bio-oil continued to replace fossil oil; new waste-incineration CHPs were constructed; and one of the largest wood chip-fired CHP plants in the world was commissioned in 2016. Even though the production of district heating has roughly doubled since 1980, the system's CO<sub>2</sub> emissions have been cut by one third.

There is also the system's first negative-emission plant, which produces biochar and heat. Biochar comprises stable carbon compounds and is used as a soil amendment that improves fertility while concurrently sequestering carbon. The plant's negative emissions are in the range of 225 tonnes of CO<sub>2</sub> per year from a centennial perspective—insignificant, but still groundbreaking.

Though the stability of biochar needs more research, according to it has been conservatively estimated that 80% of the carbon in biochar remains after 100 years, the analysis of Wang, Xiong, and Kuzyakov (2016).

**Figure 7-5 | The biochar production plant in Stockholm. Its emissions are negative with more than 100 g of CO<sub>2</sub> removed per kWh of heat produced.**



Photo: Kari Kohvakka and Stockholm Vatten och Avfall.

## **Present day: On the road to GHG neutrality by 2030**

Arriving in the present, the system's GHG emissions have been cut by approximately three times per unit of district heating produced since 1980. The current sources of GHG emissions are:

- remaining fossil fuels
- the fossil-origin part of incinerated waste
- production and transportation of fossil and biomass fuels
- dinitrogen oxide and methane
- refrigerant leakage

The two first bullet points are described in more detail below.

### **Moving away from fossil fuels**

One necessary step toward neutrality is to decommission the last fossil production units. At a glance this might seem simple, but it is not. A one sided decommissioning would create a lack production capacity.

The remedy is to replace the fossil plants with new units using renewable fuels, which requires major investments and considerable time. Some such investments have been made in the last decade and more are upcoming, and the board of Stockholm Exergi has decided to take the last large fossil unit (i.e., the PFBC plant) out of operation in 2022.

Thereafter, the only remaining pure fossil fuel consumed will be oil in peak-load and backup boilers operated only in emergencies or during very cold weather. These units will generate insignificant emissions and are not discussed further here; the fossil part of the waste burned is another matter, however.

### **Reducing fossil waste**

As plastics are versatile and useful materials, they have become incorporated into our everyday lives. When shopping at the supermarket it is hard to avoid plastic packaging. In hospitals, there is a need for one-use syringes and other useful items that are difficult to produce in other materials. The list of applications could go on and on.

Reducing the fossil part of waste is complex. Around 40% of the energy in waste is of fossil origin, of which approximately 70% is plastics (Erselius, 2017). The other fossil part consists of, for example, oil residues, textiles, and rubber. Moreover, waste is not a single homogenous fraction: there is municipal waste, demolition waste, industrial waste, etc.

Reducing the fossil content of waste will require commitment from society as a whole. The challenge is daunting, as described in a recent report from the City of Stockholm (Rylander, 2017). The problem must be addressed at the three top levels of the EU waste hierarchy (EU, 2018), with incineration being level four: society must use less plastic (level 1), use plastic products with longer lifetimes that can be re-used (level 2), and use plastics that can be recycled (level 3). The other option is to move toward bio-based plastics.

A possible part of the solution that Stockholm Exergi and the Stockholm Water and Waste Company are considering is to pre-sort municipal waste using near infrared (NIR) technology. This would reduce by 75% the amount of plastic in municipal waste that goes directly to incineration.

### **Remaining obstacles to achieving climate neutrality by 2030**

After the PFBC unit is taken out of operation by 2022, two obstacles will remain to closing in on zero emissions. Unsurprisingly, these are the production and transportation of fuels and the fossil parts of the incinerated waste. Though these obstacles are not wholly within the control of Stockholm Exergi, things can nevertheless be done to address them. Facilities for plastic sorting can be installed, as described above. There is also the option of requiring the use of renewable-energy vehicles for producing and transporting fuels to the district heating system plants.

All the above measures are foreseen to halve the GHG emissions between 2017 and 2023, when emissions will be one sixth per unit of energy compared with 1980. From then on, the path is more uncertain. For the energy production to become truly carbon neutral, negative emissions will be needed.

## Scenario for below-zero emissions by 2040

When neutral emissions of GHGs are close to being realized, the only way to improve climate performance further is by means of negative emissions. This section describes one possible scenario for the Stockholm district heating system. First, there is a need to decide which NETs are suitable to incorporate into district heating.

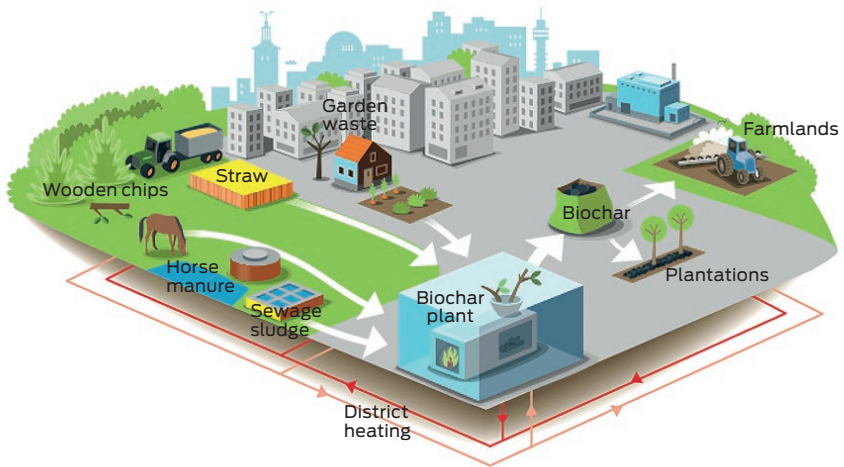
While BECCS is certainly the main focus of this publication, a wider range of NETs is being discussed globally. Among them are direct air capture (DAC), reforestation and afforestation, enhanced mineral weathering, ocean fertilization, biochar, and soil carbon sequestration (Minx et al., 2018). All these techniques have their limitations, as well as advantages and disadvantages, as discussed by, for example, Smith et al. (2015) and Easac (2018).

Alongside BECCS, biochar will also be considered here, since its production generates heat that can be recovered in the district heating system.

### Biochar in Stockholm

Biochar production is a way of capturing CO<sub>2</sub> and storing it as stable carbon compounds in soil. For a long time, charcoal (similar to biochar) was produced in charcoal kilns or in charcoal stacks, and the remnants were used as a soil enhancer, as observed by Linnaeus (1734). Today, modern techniques make it possible to produce biochar under more controlled conditions (Weber & Quicker, 2018). Biochar production can be deployed at different scales, such as individual households, farms, or industrial installations. BECCS, on the other hand, will likely rely on large point sources of biogenic CO<sub>2</sub> emissions, since the considerable investment and infrastructure needs will make small plants infeasible (Honegger & Reiner, 2018). One particular strength of biochar is that it contributes to both of the main climate strategies, i.e., mitigation and adaptation; for example, its soil-enhancing properties can help retain water during prolonged droughts (Sundberg, 2018).

As mentioned before, biochar production has already been introduced in Stockholm by the Stockholm Water and Waste Company in cooperation with the municipality and Stockholm Exergi. A pilot plant has been operating since

**Figure 7-6 | Residual waste streams from society could be used for biochar production.**

2017, converting garden waste into biochar and heat. It has negative emissions and removes more than 100 grams of CO<sub>2</sub> for every kWh of district heating produced. This concept could be further developed.

A cautious first step currently being investigated by Stockholm Exergi is to establish a plant producing approx. 10,000 tonnes of biochar every year. The input material would be garden waste, horse manure, and wood chips. A second and much larger unit has also been investigated. The unit is foreseen to use 500,000 tonnes of secondary wood fuels as input every year. This will create a CO<sub>2</sub> sink of 120 000 tonnes annually with a centennial perspective (Azzi, 2018). The fuel capacity of this second unit is in between the two wood chip fired CHP plants currently operated by Stockholm Exergi.

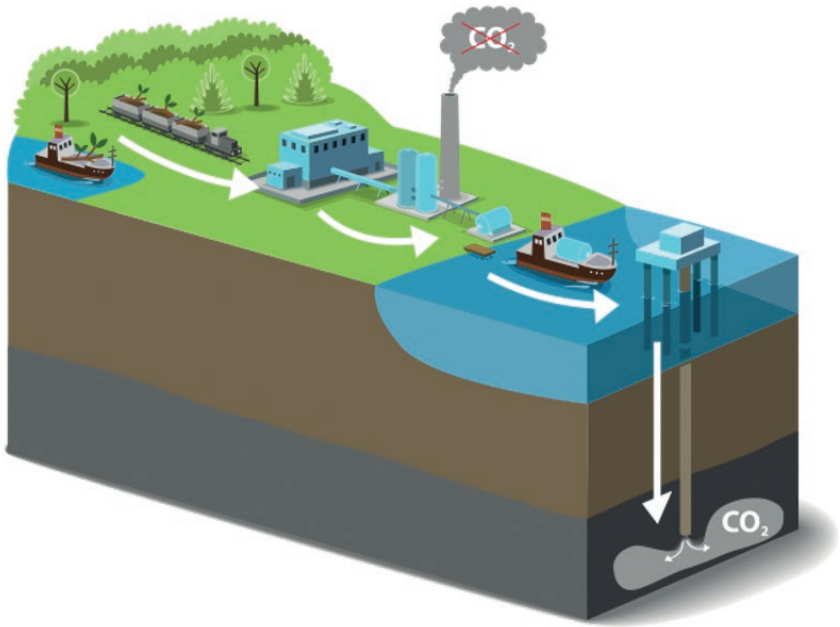
## BECCS in Stockholm

BECCS as a concept is simple. Carbon dioxide generated when converting biomass into energy is captured and stored permanently underground. The technique is somewhat familiar to Stockholm Exergi, as from 1973 to 2011 the refinery producing city gas separated out CO<sub>2</sub> by means of absorption with potassium carbonate. In addition, the same technology was tested at a small

scale on the PFBC coal-fired boiler from 2007 to 2009. The test results indicated a capture rate of more than 98% of the CO<sub>2</sub> in the flue gases (Bryngelsson & Westermark, 2009).

Internationally, BECCS is a concept that encompasses both the conversion

**Figure 7-7 | The concept of bioenergy carbon capture and storage (BECCS). Biogenic CO<sub>2</sub> emissions are captured and stored permanently underground.**



of biomass into energy and the subsequent capture of CO<sub>2</sub> (Smith et al., 2015). In Stockholm, the energy conversion part of the process is already in place, which will reduce the investment cost. Apart from the cost, several other factors affect the threshold for investing in BECCS plants, as pointed out by Honnegger and Reiner (2018) and Linde (2017). Here, the most important ones will be discussed.

BECCS can be realized in different contexts, and concerns have been raised



that the use of land for cultivating fuel crops might compete with food production, reducing food security. In Stockholm, the fuel is based on secondary wood in the form of forestry industry residues, so this point is of less concern.

The CO<sub>2</sub>-capturing process will consume electrical and thermal energy, incurring a loss of efficiency. In Stockholm, the plants using biomass produce both electricity and heat, opening up the possibility of recovering expended electric power as heat. This possibility requires further investigation and research before any definitive conclusions can be drawn.

Access to stable long-term storage is vital. In Norway, CO<sub>2</sub> has been stored for more than 20 years (SGU, 2017), and there is an ongoing project to open up another storage site. From a global perspective, transporting CO<sub>2</sub> to the North Sea has to be considered a relatively near-at-hand solution. There are options for storage in Sweden as well, but no definitive plans have been made to exploit them.

Most plants decrease in cost per unit of fuel being processed as their scale

**Figure 7-8 | Värtaverket, the prime candidate for BECCS in Stockholm**



Photo: Stockholm Exergi.



increases. BECCS is no exception. Scale also affects transportation costs in a positive way, as larger ships can be used. The Värtaverket CHP facility, the prime candidate for BECCS, is the largest point source of biogenic emissions in Stockholm. Assuming a capture rate of 97%, 800,000 tonnes of CO<sub>2</sub> can be captured from it every year. Another advantage is Värtaverket's location by the sea. Ships can dock in the vicinity and the necessity of long pipelines are eliminated. This lowers the overall cost of transportation.

The next candidates for CCS are existing or new waste incineration units, where the biogenic fraction of the fuel will result in negative emissions. In the calculations, a new incineration unit releasing approximately 450,000 tonnes of CO<sub>2</sub> has been considered.

## The Stockholm district heating system in 2040

Figure 7-2 shows the emissions from Stockholm's district heating system if the scenario outlined in this chapter is followed. The net total negative emissions could amount to around 1,000,000 tonnes of CO<sub>2</sub> every year.<sup>4</sup>

## Policy requirements to realize negative emissions

For a policy to be effective, it needs to have certain basic characteristics: it should have a longevity that gives enough security for investors; it should cover enough costs to sufficiently lower the decision threshold; and political support should be strong enough to reassure investors (Sandén, 2005).

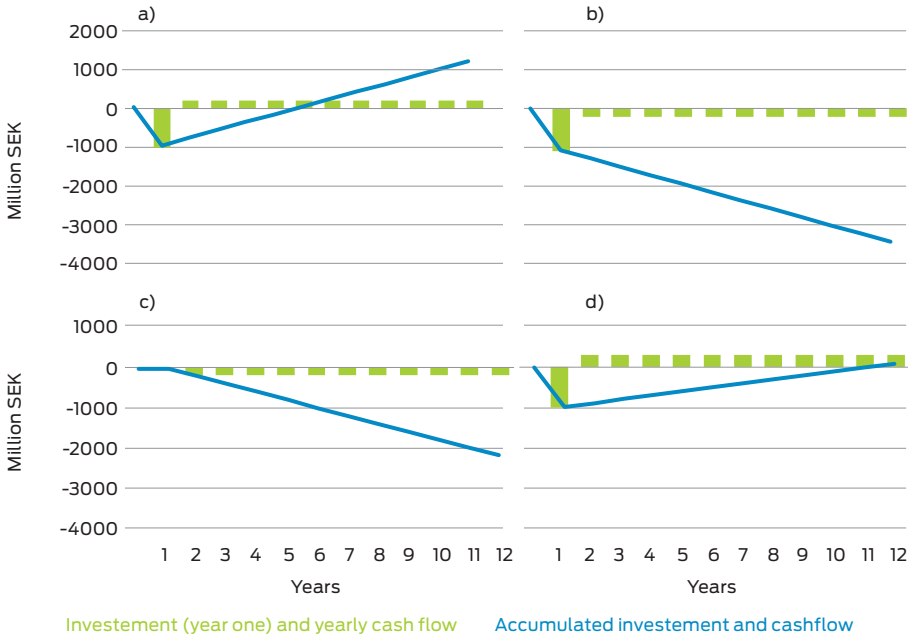
Stockholm Exergi regularly makes large, long-term investments with a usual

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<sup>4</sup> The GHG emissions in this chapter have been calculated using the current best knowledge of the quantities involved and standard methods as far as possible. Where data for minor items are lacking, extrapolations and estimates have been used. The data used are mainly from Stockholm Exergi and LCA databases. The emission factors of fuels were obtained from the Swedish Environmental Protection Agency and Värmemarknadskommittén (VMK). Emissions are either calculated or taken as reported in the EU-ETS system. Calculations of GHG emissions include these sources: production and transportation of fuels, conversion of fuel to energy, leakage of refrigerants, consumed electricity, production and transportation of consumables, and transportation of biochar and CO<sub>2</sub>. Excluded from calculations at this point are: transportation and deposit of ashes and other waste from operations (less than 0.1% of the total), secondary effects of using biochar in the agricultural sector, and secondary effects of power generation. Power produced would in reality displace other production with higher emissions.

It has been assumed that known and discussed national and EU material recycling targets will be met in 2030. More challenging targets has been assumed after that. Modest reductions in emissions from production and transportation of fuels has been assumed in 2030 and beyond.

**Figure 7-9 | The diagrams show combinations of investments and policies: a) typical investment in a plant that generates cash flow covering the investment and keeping the investing company profitable; b) investment in adding a BECCS unit to an existing boiler, which generates no additional profit; c) investment in adding a BECCS unit to an existing boiler in combination with support for 100% of the investment cost, which generates no additional profit; and d) investment in adding a BECCS unit to an existing boiler in combination with support for operational cost, which generates moderate additional profit.**



depreciation period of 25 years. For a typical investment, the yearly net income should give a payback period of approximately seven years and have a net present value that keeps the company profitable (see Figure 7-9a). High investments thus need to yield high yearly net incomes.

In the eyes of the world, BECCS is a complete package incorporating a biomass plant for heat and electricity production as well as equipment to remove  $\text{CO}_2$  (Smith et al., 2015). From this perspective, if applied in a strict sense, the added cost of  $\text{CO}_2$  removal can be financed by the income from new heat and power production. For Stockholm Exergi and many other operators, the case is likely to be viewed differently, since they already own the first part of the

package (i.e., the production plant). Adding gas removal will incur the burden of additional investment costs and a yearly cost of operation (see Figure 7-9b). This leads to the conclusion that support for operational costs is essential, since supporting investment costs still give a negative net present value, as shown in Figure 7-9c.

Financial policy support must cover the yearly operational costs as well as financing the investment cost (see Figure 7-9d). If a policy does not support operational costs, other incomes generated in new ways will be required; for instance, these incomes could come from a larger market share caused by the investment in BECCS or a higher product price on the heat and electricity produced.

Barring such innovative and possibly unpredictable incomes, it is difficult to see any enterprise investing in BECCS without support of operational costs.

## Conclusions

It has been shown that negative emissions will likely be required in order to meet climate goals at all levels. This applies equally to the Paris Agreement, the Swedish climate framework, and the company Stockholm Exergi, which is striving to be climate neutral.

District heating systems could be pioneers in the realm of negative emissions. Technically, they could do this using BECCS and biochar production; commercially, however, the challenges are much greater, and policies supporting operational costs will be needed if BECCS is to be realized at scale.

Gregory et al. (2018) have demonstrated that negative-emission technologies must be mass deployed globally by 2030 if any of the 2°C scenarios are to be met. After 2030, NETs will have to be scaled up rapidly. Despite the urgency, policies are lacking.

If extrapolated to all district heating systems in Europe, the theoretical potential of NETs is roughly 80 million tonnes of CO<sub>2</sub> removal every year. This assumes that all systems in Europe reach the same performance as in Stock-

holm, calculated per energy unit produced.

Finally, it could be said that not equipping existing biogenic emission sources with BECCS is a lost opportunity for mitigation. It could also be argued that adding CCS to bioenergy is better utilisation of resources.

## Chapter 8

# Conclusions: From global potentials to domestic realities

Mathias Fridahl

**This book explores** some of the many layers involved in moving from highly theoretical projections of the global technical potentials of bioenergy with carbon capture and storage (BECCS) to present-day realizable potentials on the domestic Swedish market.

The key messages emerging from this journey across scales are as follows:

**1. BECCS is a key mitigation technology in climate scenarios.**

Nearly all climate scenarios formulated in the last decade that are compatible with a likely chance of limiting global warming to 2°C deploy BECCS. In most cases, the scale of deployment is substantial.

**2. The theoretical potential should be interpreted cautiously.**

Integrated assessment modelers insist that they are dealing with projections, not predictions. Furthermore, international climate policymakers are of the view that BECCS should be a low investment priority. Unambitious contemporary mitigation plans combined with the low priority on investing in BECCS development is not aligned with the scenarios' cost-optimized pathways, in which BECCS already features prominently by 2030 and at a large scale by 2050.

3. **While scenarios should be viewed cautiously, contemporary European point sources of biogenic CO<sub>2</sub> indicate a substantial potential for BECCS.** The European pulp and paper industry emitted approximately 60–66 Mt of biogenic CO<sub>2</sub> in 2015. To a lesser extent, there are also indications of a potential to capture biogenic CO<sub>2</sub> from the production of electricity, heat, and biofuels. Sweden has one of Europe’s greatest potentials, with several point sources well above 0.5 MtCO<sub>2</sub> in size.
4. **On the other hand, Applying BECCS seems most suitable on existing point sources of biogenic CO<sub>2</sub>.** Extending biomass production for BECCS is more complicated and introduces goal conflicts, for example related to competition for land, fertilizers, and water.
5. **Existing policy incentives for BECCS are almost completely lacking.** This indicates that the climate scenarios’ projected large-scale deployment of BECCS is detached from reality. While some policy instruments have established funding for BECCS RD&D sufficient to cover part or all of the incremental capital expenditures, they fail to create market pull that allows revenues to cover operational expenditures. Contradictory policies at different scales of the multilevel climate governance system also create uncertainty and thus impede investments.
6. **The lack of policy incentives puts “sticks in the wheel” of businesses actively considering BECCS investments.** For Swedish actors interested in realizing the high Swedish potential for BECCS, policy objectives do matter. UN, EU, and Swedish climate policy objectives indeed influence companies to get involved in planning for negative emissions. Developing BECCS to a commercial scale will take individual businesses a long time, in the order of a decade, and today’s lack of policy instruments covering operational expenditures

actively prevents interested actors from making affirmative investment decisions. Although there is currently no supply of negative emissions from BECCS, policymakers should refrain from using this as an argument for holding back instruments that could create demand for them. With such instruments, supply is more likely to emerge, although it will take time.

While R&D into BECCS has previously been framed as a slippery slope triggering objectionable consequences, such as negative impacts on food security globally, the core message of this book echoes the sentiments of Rob Bellamy, presented in chapter 5, that realizing the projected potential of BECCS, even if only partly, should instead be seen as a cumbersome and long uphill struggle.

This book has highlighted the many caveats involved in moving from the theoretical potentials at the global scale to the practically realizable, economically viable potentials facing businesses investment units at the local scale.

# References

- AlcoGroup S.A.** (2018). *Production - AlcoGroup*. [www.alcogroup.com/production](http://www.alcogroup.com/production)
- Anderson, K.** (2015). Duality in climate science. *Nature Geoscience* 8, 898.
- Anderson, K., and Peters, G.** (2016). The trouble with negative emissions. *Science* 354, 182–183.
- Arthur, W.** (1989). Competing technologies, increasing returns, and lock-in by historical events. *Economic Journal* 99, 116 – 131.
- Azar, C., Johansson, D. J. A., and Mattsson, N.** (2013). Meeting global temperature targets—the role of bioenergy with carbon capture and storage. *Environmental Research Letters* 8(3), 034004.
- Azzi, E.** (2018). Presentation at International conference on Negative CO<sub>2</sub> Emissions May 22–24. System analysis of large-scale biochar production and use for negative CO<sub>2</sub> emissions in Sweden.
- Banerjee, B., Collins, G., Low, S. and Blackstock, J.** (2013). *Scenario planning for solar radiation management: scenario workshop report*. Yale Climate and Energy Institute: New Haven.
- Barrett, S.** (2008). The incredible economics of geoengineering. *Environmental and Resource Economics* 39, 45–54.
- Bataille, C., Åhman, M., Neuhoff, K., Nilsson, L. J., Fishedick, M., Lechtenböhmer, S., . . . Rahbar, S.** (2018). A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the Paris Agreement. *Journal of Cleaner Production* 187, 960–973.
- Beal, C., Archibald, I., Huntley, M., Greene, C. and Johnson, Z.** (2018). Integrating algae with bioenergy carbon capture and storage (ABECCS) increases sustainability. *Earth's Future* 6, 524–542.
- Beck, B., & Krueger, T.** (2016). The epistemic, ethical, and political dimensions of uncertainty in integrated assessment modeling. *WIREs Climate Change* 7, 627–645.
- Beck, S. and Mahony, M.** (2018) The politics of anticipation: the IPCC and the negative emissions technologies experience. *Global Sustainability* 1, e8.
- Bellamy, R.** (2018). Incentivise negative emissions responsibly. *Nature Energy*.
- Bellamy, R. and Healey, P.** (2018). Slippery slope or uphill struggle? Expert scenarios of geoengineering research and development. *Environmental Science and Policy* 83, 1–10.



- Bellamy, R., Chilvers, J., Vaughan, N. and Lenton, T.** (2012). A review of climate geoengineering appraisals. *WIREs Climate Change* 3, 597–615.
- Bemelmans-Vidéc, M.-L., Rist, R.C., Vedung, E.O.** (2010). *Carrots, sticks, and sermons: Policy instruments and their evaluation*. New Brunswick and London: Transaction Publishers.
- Bhatti, R. S., and Ruck, N.** (2018). *Cost and technical requirements for transport of carbon dioxide with carbon storage*. Brussels: European Technology Platform for Zero Emission Fossil Fuel Power Plants.
- Bodansky, D.** (1996). May we engineer the climate? *Climatic Change* 33, 309–321.
- Bodle, R., Oberthür, S., Donat, L., Homann, G., Sina, S. and Tedsen, E.** (2014). *Options and proposals for the international governance of geoengineering*. Ecologic Institute: Berlin.
- Boettcher, M., Gabriel, J. and Harnisch, S.** (2015). *Scenarios on stratospheric albedo modification in 2030*. Priority Programme 1689 of the German Research Foundation: Hamburg.
- Bryngelsson, M. and Westermark, M.** (2009). CO<sub>2</sub> capture pilot test at a pressurized coal fired CHP plant. *Energy Procedia* 1, 1403–1410.
- Buck, H. J.** (2016). Rapid scale-up of negative emissions technologies: social barriers and social implications. *Climatic Change* 139(2), 155–167.
- Börjesson, P., Hansson, J., Berndes, G.** (2017). Future demand for forest-based biomass for energy purposes in Sweden. *Forest Ecology and Management* 383, 17–26.
- Cairns, R.** (2014). Climate geoengineering: issues of path-dependence and socio-technical lock-in. *WIREs Climate Change* 5, 649–661.
- Creutzig, F. N. H., Ravindranath, G. Berndes, S., Bolwig, R., Bright, F., & Cherubini, F., et al. (2015). Bioenergy and climate change mitigation: an assessment. *Global Change Biology: Bioenergy* 7, 916–944.
- Collingridge, D.** (1980). *The social control of technology*. Francis Pinter: New York, USA.
- David, P.** (2001). “Path dependence, its critics and the quest for ‘historical economics’”. In: Garrouste, P. and Ioannides, S. (Eds.). *Evolution and path dependence in economic ideas: past and present*. Edward Elgar: Cheltenham, UK.
- Di Lucia, L., and Ericsson, K.** (2014). Low-carbon district heating in Sweden – Examining a successful energy transition. *Energy Research and Social Science* 4, 10–20.
- Dixon, T., Garrett, J., Kleverlaan, E.** (2014). Update on the London Protocol – Developments on Transboundary CCS and on Geoengineering. *Energy Procedia* 63, 6623–6628.
- Dixon, T., Leamon, G., Zakkour, P., Warren, L.** (2013). CCS Projects as Kyoto Protocol CDM Activities. *Energy Procedia* 37, 7596–7604.
- Douglas, M.** (1986). *How institutions think*. Oxon, UK: Routledge.
- Drax Group.** (2018). *Drax to pilot Europe’s first carbon capture storage project*. [https://www.drax.com/press\\_release/drax-to-pilot-europes-first-carbon-capture-storage-project-beccs/](https://www.drax.com/press_release/drax-to-pilot-europes-first-carbon-capture-storage-project-beccs/)

- Duscha, V., Ríó, P.d.** (2017). An economic analysis of the interactions between renewable support and other climate and energy policies. *Energy & Environment* 28, 11–33.
- EASAC.** (2018). Negative emission technologies: What role in meeting Paris Agreement targets?
- Emmenegger, L., et al.** (2012). Fossil and biogenic CO<sub>2</sub> from waste incineration based on a yearlong radiocarbon study. *Waste Management* 32(8): 1516–1520.
- Erselius, G.** (2017). Fossil andel i verksamhetsavfall.
- Erselius, G.** (2018). Klimatpositiv fjärrvärme med biokol.
- EU** (2018). *Directive 2008/98/EC on waste (Waste Framework Directive)*. Brussels: European Union.
- European Bioplastics.** (2018). *Bioplastics market data 2017*. Berlin: European Bioplastics.
- European Commission.** (2017). *EU-28 ethyl alcohol balance sheet for 2016*. Luxembourg: Office for Official Publications of the European Communities.
- Fajardy, M. and Mac Dowell, N.** (2017). Can BECCS deliver sustainable and resource efficient negative emissions? *Energy Research and Social Science*, 10, 1389–1426.
- Fridahl, M., and Lehtveer, M.** (2018). Bioenergy with carbon capture and storage (BECCS): Global potential, investment preferences, and deployment barriers. *Energy Research and Social Science*, 42, 155–165.
- Fuss, S., Canadell, J. G., Peters, G. P., Tavoni, M., Andrew, R. M., Ciais, P., . . . Nakicenovic, N.** (2014). Betting on negative emissions. *Nature Climate Change*, 4(10), 850–853.
- Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., . . . Minx, J., C. .** (2018). Negative emissions—Part 2: Costs, potentials and side effects. *Environmental Research Letters*, 13(6), 063002.
- GAO** (2011). *Climate Engineering: technical status, future directions, and potential responses*. United States Government Accountability Office Center for Science, Technology, and Engineering Report to Congressional Requester.
- Geden, O.** (2018). Politically informed advice for climate action. *Nature Geoscience*, 11, 380–383.
- Geden, O.** (2015). Climate Advisers must maintain integrity. *Nature* 521, 27–28.
- Geden, O., Scott, V., and Palmer, J.** (2018). Integrating carbon dioxide removal into EU climate policy: Prospects for a paradigm shift. *Wiley Interdisciplinary Reviews: Climate Change*, 9(4), e521.
- Gough, C., Garcia-Freites, S., Jones, C., Mander, S., Moore, B., Pereira, C., . . . Welfle, A.** (2018). Challenges to the use of BECCS as a keystone technology in pursuit of 1.5°C. *Global Sustainability*, 1, e5.
- Gough, C. and Upham, P.** (2001). Biomass energy with carbon capture and storage (BECCS or Bio-CCS). *Greenhouse Gases: Science and Technology* 1(4): 324–334.
- Gregory, F. N., Max, W. C., Felix, C., Sabine, F., Jens, H., Jérôme, H., . . . Pete, S.** (2018). Negative emissions—Part 3: Innovation and upscaling. *Environmental Research Letters*, 13(6), 063003.

- Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D. L., ... Valin, H.** (2018). A low energy demand scenario for meeting the 1.5°C target and sustainable development goals without negative emission technologies. *Nature Energy*, 3(6), 515–527.
- Grönkvist, S., Grundfelt, E., Sjögren, H.,** (2008). *CO<sub>2</sub>-avskiljning i Sverige* [Carbon capture in Sweden]. Ångpanneföreningens Forskningsstiftelse and the Swedish Environmental Protection Agency, Stockholm.
- Haraguchi, M., Liu, R., Randhawa, J., Salz, S., Schäfer, S., Sharma, M., Chan Schifflet, S., Suzuki, A. and Yuan, Y.** (2015). *Human intervention in the Earth's climate: the governance of geoengineering in 2025+*. Global Governance Futures: Robert Bosch Foundation Multilateral Dialogues.
- Harper, A. B., Powell, T., Cox, P. M., House, J., Huntingford, G., Lenton, T. M., ... Shu, S.** (2018). Land-use emissions play a critical role in land-based mitigation for Paris climate targets. *Nature Communications*, 9(1), 2938.
- Heck, V., Gerten, D., Lucht, W. and Popp, A.** (2018). Biomass-based negative emissions difficult to reconcile with planetary boundaries. *Nature Climate Change*, 8, 151–155.
- Honegger, M., and Reiner, D.** (2018). The political economy of negative emissions technologies: consequences for international policy design. *Climate Policy*, 18(3), 306–321.
- Howlett, M.** (2011). *Designing Public Policies: Principles and Instruments*. London and New York: Routledge.
- Hubert, AM., Kruger, T. and Rayner, S.** (2016). Code of conduct for geoengineering. *Nature*, 537, 488.
- Humphreys, D.** (2011). Smoke and mirrors: some reflections on the science and politics of geoengineering. *Journal of Environment and Development*, 20, 99–120.
- Hybrit.** (2018). [www.hybritdevelopment.com](http://www.hybritdevelopment.com)
- IEA.** (2011). *Potential for biomass and carbon capture and storage*. Celtenham: International Energy Agency.
- IPCC.** (2014). *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Jamieson, D.** (1996). Ethics and intentional climate change. *Climatic Change*, 33, 323–336.
- Jefferson, A.** (2014). Slippery slope arguments. *Philosophy Compass*, 9, 672–680.
- Johansson, D., Rootzén, J., Berntsson, T., and Johnsson, F.** (2012). Assessment of strategies for CO<sub>2</sub> abatement in the European petroleum refining industry. *Energy* 42(1): 375–386.
- Johnke, B.** (2003). *Emissions From Waste Incineration. Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*. Geneva: Intergovernmental Panel on Climate Change.

- Jones, F.C., Blomqvist, E.W., Bisailon, M., Lindberg, D.K., Hupa, M.** (2013). Determination of fossil carbon content in Swedish waste fuel by four different methods. *Waste Management and Research* 31: 1052–1061.
- Jönsson, J.** (2011). *Analysing different technology pathways for the pulp and paper industry in a European energy systems perspective*. (PhD Thesis). Gothenburg: Heat and Power Technology Department of Energy and Environment, Chalmers University of Technology.
- Kindermann, G., et al.** (2014). BECCS in South Korea—Analyzing the negative emissions potential of bioenergy as a mitigation tool. *Renewable Energy* 61: 102–108.
- Kheshgi, H.S., and Prince, R.C.** (2005). Sequestration of fermentation CO<sub>2</sub> from ethanol production. *Energy* 30(10): 1865–1871.
- Lantmännen.** (2018). *Lantmännens Årsrapport*. Stockholm: Lantmännen.
- Levihn, F.** (2017). CHP and heat pumps to balance renewable power production: Lessons from the district heating network in Stockholm. *Energy*, 137, 670–678.
- Le Quéré, C., Andrew, R. M., Friedlingstein, P., Sitch, S., Pongratz, J., Manning, A. C., . . . Zhu, D.** (2018). Global Carbon Budget 2017. *Earth Syst. Sci. Data*, 10(1), 405–448.
- Lin, A.** (2009). Geoenvironmental governance. *Issues in Legal Scholarship*, 8, 1539–8323.
- Linde, L.** (2017). *Implementation of BECCS in a polygeneration system: A techno-economic feasibility study in the district heating network of Stockholm*. (Master thesis). Stockholm: KTH Royal Institute of Technology.
- Linnaeus, C.** (1734). Dalaresa.
- Lode, E.** (1999). Slippery slope arguments and legal reasoning. *California Law Review*, 87, 1469–1544.
- Low, S.** (2017). Engineering imaginaries: anticipatory foresight for solar radiation management governance. *Science of the Total Environment*, 580, 90–104.
- Martínez de Alegría, I., Fernández-Sainz, A., Alvarez, I., Basañez, A., del-Río, B.** (2017). Carbon prices: Were they an obstacle to the launching of emission abatement projects in Spain in the Kyoto Protocol period? *Journal of Cleaner Production* 148, 857–865.
- Mistra Carbon Exit.** (2018). Nio budskap från Mistra Carbon Exit - Vägen till ett koldioxidneutralt samhälle 2045 Januari 2018
- MIT.** (2016). *White Rose Project Fact Sheet*. Cambridge: Massachusetts Institute of Technology.
- Minx, J. C., Lamb, W. F., Callaghan, M. W., Fuss, S., Hilaire, J., Creutzig, F., . . . Del Mar Zamora Dominguez, M.** (2018). Negative emissions—Part 1: Research landscape and synthesis. *Environmental Research Letters*, 13(6), 063001.
- McCollum, D. L., Wilson, C., Pettifor, H., Ramea, K., Krey, V., Riahi, K., . . . Fujisawa, S.** (2017). Improving the behavioral realism of global integrated assessment models: An application to consumers' vehicle choices. *Transportation Research Part D: Transport and Environment*, 55, 322–342.

- McCollum, D. L., Zhou, W., Bertram, C., de Boer, H.-S., Bosetti, V., Busch, S., . . . Riahi, K.** (2018). Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. *Nature Energy*, 3(7), 589–599.
- Morrow, D., Kopp, R. and Oppenheimer, M.** (2009). Toward ethical norms and institutions for climate engineering research. *Environmental Research Letters*, 4, 045106.
- Mohn, J. Szidat, S., Fellner, J., Rechberger, H., Quartier, R., Buchmann, B., and Emmenegger, L.** (2008). Determination of biogenic and fossil CO<sub>2</sub> emitted by waste incineration based on <sup>14</sup>CO<sub>2</sub> and mass balances. *Bioresource Technology* 99(14): 6471–6479.
- Naturvårdsverket.** (2017). *Bilaga 1 till beslutsprotokoll med diarienummer NV-07819-17*. Retrieved from: [www.naturvardsverket.se/upload/stod-i-miljoarbetet/vagledning/avfall/Naturvardsverket-hanvisningsvarden-for-blandat-avfall.pdf](http://www.naturvardsverket.se/upload/stod-i-miljoarbetet/vagledning/avfall/Naturvardsverket-hanvisningsvarden-for-blandat-avfall.pdf)
- Olsen, R.** (2011). *Geoengineering for decision makers*. Science and Technology Innovation Program, Woodrow Wilson International Center for Scholars: Washington DC, USA.
- O’Neill, B. C., Kriegler, E., Riahi, K., Ebi, K. L., Hallegatte, S., Carter, T. R., . . . van Vuuren, D. P.** (2014). A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Climatic Change*, 122(3), 387–400.
- Pacca, S.A., Moreira, J.R., Romeiro, V., Fuss, S., and Kraxner, F.** (2016). BECCS potential in Brazil: Achieving negative emissions in ethanol and electricity production based on sugar cane bagasse and other residues. *Applied Energy* 179: 55–63.
- Pascala, S. and Socolow, R.** (2004). Stabilization wedges: solving the climate problem for the next 50 years with current technologies. *Science*, 305, 968–972.
- Peters, G. P., and Geden, O.** (2017). Catalysing a political shift from low to negative carbon. *Nature Climate Change*, 7, 619.
- Pindyck, R., S.** (2013). Climate Change Policy: What Do the Models Tell Us? *Journal of Economic Literature*, 51, 860–872.
- Popp, A., Calvin, K., Fujimori, S., Havlik, P., Humpenöder, F., Stehfest, E., . . . Vuuren, D. P. v.** (2017). Land-use futures in the shared socio-economic pathways. *Global Environmental Change*, 42, 331–345.
- Rayner, S.** (2017). “Climate engineering: responsible innovation or reckless folly?” In: Asveld, L., van Dam-Mieras, R., Swierstra, T., Lavrijssen, S., Linse, K. and van den Hoven, J. (Eds.). *Responsible innovation 3: A European Agenda?* Cham, Switzerland: Springer.
- Rylander, F.** (2018). *Minskad energiåtervinning av fossil plast*. Stockholm: Stockholms stad.
- Sandén, B. A. A., Christian.** (2005). 05/02802 Near-term technology policies for long-term climate targets-economy wide versus technology specific approaches. *Fuel and Energy Abstracts*, 46(6), 407.

- SCB.** (2018). <http://www.scb.se/hitta-statistik/statistik-efter-amne/transporter-och-kommunikationer/vagtrafik/fordonsstatistik/>
- Schwanitz, V. J., Longden, T., Knopf, B., and Capros, P.** (2015). The implications of initiating immediate climate change mitigation — A potential for co-benefits? *Technological Forecasting and Social Change*, 90, 166–177.
- SGU.** (2017). *Geologisk lagring av koldioxid i Sverige: Lägesbeskrivning avseende förutsättningar, lagstiftning och forskning samt olje- och gasverksamhet i Östersjöregionen*. Uppsala: Geological Survey of Sweden.
- Shishlov, I., Morel, R., Bellassen, V.** (2016). Compliance of the Parties to the Kyoto Protocol in the first commitment period. *Climate Policy* 16, 768–782.
- Smith, P., Davis, S. J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., . . . Yongsung, C.** (2015). Biophysical and economic limits to negative CO<sub>2</sub> emissions. *Nature Climate Change*, 6, 42.
- Solis, M.** (2018). *Potential of chemical recycling to improve the recycling of plastic waste*. (Master thesis). Stockholm: KTH Royal Institute of Technology.
- Stigson, P., Haikola, S., Hansson, A., Buhr, K.** (2016). Prospects for Swedish acceptance of carbon dioxide storage in the Baltic Sea: Learning from other energy projects. *Greenhouse Gases: Science and Technology* 6, 188–196.
- Stirling, A.** (2007). *Risk, precaution and science: towards a more constructive policy debate. Talking point on the precautionary principle*. EMBO Reports, 8, 309–315.
- Stirling, A.** (2008). ‘Opening up’ and ‘closing down’: power, participation, and pluralism in the social appraisal of technology. *Science, Technology and Human Values*, 33, 262–294.
- Sun, M., Wang, Y., Shi, L. and Klemešd, J. J.** (2018). Uncovering energy use, carbon emissions and environmental burdens of pulp and paper industry: A systematic review and meta-analysis. *Renewable and Sustainable Energy Reviews* 92: 823–833.
- Sundberg, C.** (2018). *CO<sub>2</sub>-Negative Cooking and Cultivation in Smallholder Farms in Africa: the Potential Role of Pyrolysis and Biochar*. Presentation at International conference on Negative CO<sub>2</sub> Emissions May 22–24.
- UNEP** (2017), *The Emissions Gap Report 2017*. Nairobi: United Nations Environment Programme (UNEP).
- Vaughan, N. E., and Gough, C.** (2016). Expert assessment concludes negative emissions scenarios may not deliver. *Environmental Research Letters*, 11(9), 095003.
- Wang, J., Xiong, Z., and Kuzyakov, Y.** (2016). Biochar stability in soil: meta-analysis of decomposition and priming effects. *Global Change Biology: Bioenergy* 8, 512–523.
- Weber, K., and Quicker, P.** (2018). Properties of biochar. *Fuel*, 217, 240–261.
- Werner, S.** (2017). District heating and cooling in Sweden. *Energy*, 126, 419–429.
- World Bank** (2018). *State and Trends of Carbon Pricing 2018*. Washington: World Bank Group and Ecofys.
- Zürn, M. and Schäfer, S.** (2013). The paradox of climate engineering. *Global Policy*, 4, 266–277.

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# Bioenergy with carbon capture and storage

From global potentials  
to domestic realities

**The role of bioenergy** with carbon capture and storage (BECCS) in climate governance is contested. On one hand, a growing climate modeling literature concludes that the Paris Agreement's temperature goal is unlikely to be achieved without the deployment of BECCS; on the other hand, the feasibility of deploying BECCS at the scales suggested in the climate scenarios is increasingly being questioned. This book highlights the many caveats involved in moving from BECCS' global mitigation potential, as depicted in the idealized world of climate scenarios, to economically viable potentials available to investors at the business scale. It concludes that overcoming the challenges associated with realizing the theoretical potential of BECCS will be daunting, a true uphill struggle. Yet with appropriate policy incentives, BECCS may still come to play an important role in the struggle to limit global warming to well below 2°C.



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