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Article

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Research paper

Introducing BECCS through HPC to the research agenda: The case of combined heat and power in Stockholm

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ABSTRACT

In the years since COP21 in Paris, awareness of the need for carbon sinks has grown rapidly. However, policy instruments supporting a path to this target are still lacking.

Bioenergy carbon capture and storage (BECCS) may provide a way to rapidly reduce global warming. In the Nordics, much of the basic infrastructure for successful BECCS implementation is already in place. So why is not more happening?

This study provides insights to barriers and policy implications in relation to successful BECCS implementation. Though implementation could support economic growth and welfare development, the cost is relatively high for individual utilities. In the deregulated competitive heating market in the case of Stockholm, cost transfer to customers is prohibited, effectively impeding implementation. Moreover, while present national or EU-based support schemes could cover investments, the operating cost is high, so other economic policy approaches are required.

Lastly, this paper shows that BECCS on combined heat and power plants has a potential, but requires much more research. Thus it is suggested that negative emission technologies in energy systems are brought into research agendas such as the future of combined heat and power and urban multi energy systems.

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1. Introduction

The importance of negative emission technologies (NETs) for reaching COP21 targets on limiting global warming well below 2 °C is apparent. In the IPCC Fifth Assessment Report (IPCC, 2014), 101 of 116 scenarios responding to the COP21 goals included carbon sinks (Fuss et al., 2014). NETs are therefore an important complement to other climate change mitigation efforts, such as increased use of renewable energy sources (Lomax et al., 2015). This has been further emphasized by the SR15 report by IPCC (2018), where all scenarios reaching a 1.5 °C target with or without overshoot include NETs.

One promising NET is bioenergy carbon capture and storage (BECCS). Over time, good biomass processes are normally somewhat more or less climate change neutral, as the CO₂ released during biomass processing is taken up by new biomass as it grows. By capturing and storing the CO₂ from bio-based processes, CO₂ levels are actively reduced. BECCS thus has double benefits: it addresses future CO₂ emissions by adding predictable renewable energy generation offsetting fossil fuels; additionally,

BECCS addresses past emissions by reducing existing atmospheric CO₂ (Krahé et al., 2013).

BECCS is not one technology, but rather comprises many technologies, such as bio refineries and power and heat generation (Kato et al., 2017). Bioresources comprise a multitude of material sources ranging from virgin wood to the biogenic fraction of various waste streams, such as municipal solid waste (MSW) (Pour et al., 2017). Carbon-capture technologies could in turn be either part of new plant design or retrofitted to existing production units.

Given the importance of NETs, surprisingly little relevant R&D has taken place recently; for example, many projects were canceled in the European carbon capture and storage (CCS) industry from 2010 to 2015 (Billson and Purkashanian, 2017). Mander et al. (2017) discussed the fact that BECCS requires three distinct elements: (1) a biomass supply chain, (2) energy generation, and (3) transport and storage infrastructure. According to Billson and Purkashanian (2017), the many project cancellations are because the oversized infrastructure that must be in place imposes high initial costs on the first mover, acting as a barrier blocking government support. For many CCS projects (refineries excluded), CO₂ storage and transport also require capabilities external to the energy sector, resulting in a demand for cross-sector coordination (Bennet and Heidug, 2014) if projects are to succeed.

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List of abbreviations

BECCS	bio energy carbon capture and storage
CCS	carbon capture and storage
CHP	combined heat and power
DH	district heating
EUA	European emission allowance
FBC	fluidized bed combustion
GHG	greenhouse gas
HPC	hot potassium carbonate
IPCC	intergovernmental panel on climate change
MSW	municipal solid waste
NET	negative emissions technology
NPV	Net present value
PFBC	pressurized fluidized bed combustion
SE	Stockholm Exergi AB (energy utility)
SR15	IPCC special report on global warming of 1.5 °C
WSP	consultancy firm

The multi-energy system in Stockholm is interesting from this perspective. The largest actor in the system, Stockholm Exergi AB (SE), already utilizes about 6 TWh of biogenic-origin fuel for heat and electric power production (excluding bio-oils in peak and backup boilers). Three TWh of this biomass is based on wood chips from Swedish forestry industry residues; most of the rest consists of the biogenic fraction of MSW, with a smaller portion of bio-pellets. The first two steps are thus in place, and neighboring Norway has much of the knowhow and infrastructure for storage. In this respect, Stockholm is in many ways BECCS ready, “only” lacking a CO₂-capture technology integrated with existing infrastructure. Another NET, biochar produced through slow pyrolysis, is already supplying carbon-negative district heating (DH) to the Stockholm multi-energy system.

CO₂ capture using HPC process (i.e. absorber/desorber with hot potassium carbonate) has previously been tested on one of Stockholm’s combined heat and power (CHP) plants together with SARGAS (Bryngelsson and Westermark, 2009; Hetland and Christensen, 2008). From 1971 to 6 February 2011, SE also operated a gas refinery with four CO₂-scrubbing units utilizing the HPC process.¹ As a result, SE has technological familiarity with and experience of post-combustion technologies. So why is BECCS not being implemented?

This paper analyzes the situation in Stockholm and presents a roadmap of potential BECCS implementation, comparing BECCS with other measures implemented under a purported climate change mitigation agenda. Specifically, it identifies the policy implications of successful BECCS implementation in the Nordic region and provides valuable input for modeling NETs.

While there is much research on BECCS in general terms, there is an surprising absence of research on BECCS applied specifically on CHP-plants. While BECCS is related to traditional CCS, CCS research has focused on power plants. Although unconventional format for framing a problem, the following examples from searches in different databases does illustrate an issue. Doing a search for [“BECCS”] on nature.com returns 60 hits, [“combined heat and power”] 68 hits, while [“BECCS” and “CHP”] and [“combined heat and power”] provides zero hits respectively.

¹ Today, the CO₂ scrubbers of the gas refinery are ironically referred to as carbon capture and release (CCR) by some Stockholm Exergi employees.

On sciencedirect.com, covering more focused journals with a less general scope, the search string [“CCS” and “power plant”] returns over 3000 journal papers and reviews since year 2015. A similar search on [“BECCS” and “CHP”] only return 20 papers since 2015. Most of these 20 papers do not focus on the topic. For example, a paper by Moore (2017) focused on thermal hydrogen mentions BECCS and CHP, but not in the same context.

Among the few published peer-reviewed journal papers, there is some focus on the global potential and sustainability of BECCS (examples include: Tokimatsu et al., 2017; Bhawe et al., 2017). Other examples has a more regional focus, and for example the potential in Japan (Kraxner et al., 2014a) and South Korea (Kraxner et al., 2014b) has been covered.

Although scarce, some research has focused on the component or fuels available for BECCS applications. Examples include Börjesson et al. (2017) who discussed the potential future competition for biomass between different energy utilization and Beal et al. (2018) who covered how algae could be utilized as a fuel in BECCS processes. Pour et al. (2018) discussed the potential of biologically derived fractions of MSW. There use of different amine solvents in post combustion capture process has also gained some attention (e.g. Bui et al., 2017).

In the context of CHP the use of HPC has not previously been covered in academic journals, with most research focusing on amine technologies for energy generation. One study has modeled HPC in aspen, but not specifically integrated it with the heat recovery potential of CHP (Wu et al., 2018). The previous literature has neither covered the discrepancy between macro-economic performance and factors more related to business administration. This paper address this issue as well as reintroducing HPC as a technology that should not be overlooked in energy related BECCS applications. Further the paper contributes with lifting BECCS onto the 4th generation district heating agenda (see e.g. the work on 4GDH/4DH by Lund et al., 2014, where it is lacking today).

2. Background

2.1. Social vs. private costs

Almost a century ago in *The Economics of Welfare*, vol. 1, Arthur Cecil Pigou (1920), discussed how a difference between social and private costs results in the market not effectively allocating available resources. In practice, when factors relevant to society are not priced and included in market transactions, the market mechanism will lead to under or over consumption of particular goods. This has led to the now familiar “Pigouvian taxes”, but the aim of reducing the difference between private and social costs is also relevant to other policy instruments.

In the case of CCS and BECCS, many positive and negative externalities affect the short- and long-term prospects of their deployment. Krahé et al. (2013) have listed five of these, showing the complexity to which society as well as private actors must respond:

- the negative effects of greenhouse gas (GHG) emissions not reflected in market prices;
- the public good accruing from knowledge creation and innovation; for example, first movers are compensated to advance R&D and scale economies;
- asymmetrical information discourages capital markets;
- inter-firm dependence for required capabilities extends over multiple sectors; and
- imperfect competition exists though natural monopolies in transport and storage.

Accordingly, policy instruments to support CCS and BECCS development require the internalization of both negative and positive social effects. However, no financial incentives are currently in place anywhere in the world to promote electric power generation with negative emissions, as present policy either penalizes CO₂ emissions or supports zero-emission technologies (Bhave et al., 2017).

2.2. Context of Stockholm and the Nordic countries

The Nordic countries have great capabilities for successful BECCS implementation (Rydén et al., 2017; Lyngfeldt and Linderholm, 2017). Existing infrastructure for biomass/MSW supply chains and the world-leading adoption of DH systems with CHP are in place, mainly in Sweden, Finland, and Denmark. Norway is a world leader in CO₂ storage, having successfully implemented CCS since 1995 and now sequestering about 1.7 MT of CO₂ p.a. There is also potential for storing CO₂ in Sweden, but the projects are still at an early stage.

Of the different parts of a potential CCS supply chain, CO₂ transport is the most mature, as the transport of gaseous and liquid fuels in pipelines and ships is common (IEA GHG, 2013; IPCC, 2005). As a result, the choice of transport system is a matter of logistics optimization in which the amount of CO₂ relative to the distance between capture and storage favors either pipeline or ship transport. Hybrid systems are also possible, in which regional emissions are collected in transport hubs. Kjærstad et al. (2016) specifically analyzed the Nordic context, concluding that ship transport is the most economical way of transporting CO₂ in most potential cases. This is in line with Knoope et al. (2015), who concluded more generally that relatively small point sources of CO₂ and long distances, as in the case of Stockholm BECCS and Norway, favor ship transport.

Stockholm's multi-energy system is one of the most advanced worldwide, incorporating most of the elements of fourth-generation DH (Lund et al., 2014). The present system was exhaustively described, including operation and duration charts, by Levihn (2017). In practice, of the 12 TWh of DH produced in a normal year, half has biogenic origins from either biomass or the biogenic fraction of MSW. SE, the largest utility operating in the Stockholm system, has experience of carbon-capture technologies, having operated the HPC process on a local refinery between 1971 and 2011 (see Fig. 1, showing the HPC CO₂ scrubbers). One author of this paper served as both head of operations and plant manager at the refinery. Furthermore, pilot testing of the SARGAS process (simplified a HPC/Benfield process installed on a pressurized boiler) was carried out on a 400 MW pressurized fluidized bed combustion (PFBC) plant from 2007 to 2009 (Bryngelsson and Westermark, 2009; Hetland and Christensen, 2008; Levihn, 2014; Levihn et al., 2014). Since 2017, a pilot plant for biochar/DH coproduction has also been installed in the system. This plant produces about 300 tonnes of biochar p.a. (corresponding to about 750 tonnes of CO₂) while supplying about 1 GWh of DH. As such, SE has many of the capabilities required for scaling up and implementing NETs in power and DH production.

Looking specifically at a possible scenario for reducing CO₂ emissions from DH and electric power generation in the region, three major sources of CO₂ exist: the coal/biofuel PFBC unit, fossil-fuel fractions in MSW and other waste streams (mostly plastics), and fossil oil in the backup and peak boilers. The coal/biofuel plant will be phased out by the end of 2022, leaving the fossil-fuel fractions in MSW and fossil-oil peak/reserve boilers. Of the peak boilers, most are already converted to various bio-oils or solid biomass, so the total emission reduction potential from converting the remaining capacity is comparatively small.

At the largest power production site, Värtaverket, a new CHP plant, KVV8, was commissioned in 2016 with wood chips based



Fig. 1. The four HPC/Benfield CO₂ separation lines at the gas refinery in Stockholm that operated utilizing hot potassium carbonate between 1971 and 2011 (photograph taken 16 March 2018).

on forestry residues, such as tree branches and tops, as the main fuel; the plant thus utilizes secondary biomass. KVV8 is rather large with capacity for 500 MW of fuel (LHV) and access to a harbor (refer to Levihn (2017) for further data on the different types of production in the Stockholm energy system). KVV8 is a possible candidate for BECCS retrofitting. While CCS could also be considered for the MSW plants, the present units lack harbor access and are not considered for CCS within the scope of this paper.

In Sweden, seven of eight parliamentary parties have agreed on the goal of reaching net-zero GHG emissions by 2045, after which net emissions should be negative. Stockholm municipality has an even more ambitious target, aiming to be fossil-fuel free by 2040. To support this target, available CO₂ abatement options were screened in 2017 in cooperation with the consultancy firm WSP and the utility SE, which the city co-owns with the Fortum Group.

The screening considered the technical and economic feasibility of over 20 abatement options, the private cost to the city (e.g. how different options affect the city's balance sheet), as well as the calculated social cost to Sweden as a whole. The screening is available in a report from WSP (Bondemark et al., 2018), and selected results are reproduced in Table 1.

The great discrepancy between the private and social costs is obvious for many of the options listed in Table 1. What also is obvious is the large spread in economic efficiency between different options. It should be noted, however, that the definition of cost per unit of reduced CO₂ emissions fails to capture

Table 1

Selected options included in Stockholm's 2017 screening of climate change abatement potential; costs recalculated to €.

	CO2 abatement potential [ktonnes CO ₂ p.a.]	Private cost, municipality [€/tonnes CO ₂]	Social cost Sweden [€/t CO ₂]
Peak boiler fuel switching (700 MW)	50	23	61
Large energy efficiency improvements in existing buildings ^a	45	2160	2 810
Stricter energy performance new buildings (Järva) ^a	2	12	1 540
Solar municipality roofs	0,1	−340	1 920
LED street light substitution	0,4	−240	−313
Increased parking fees	18	−1740	−360
Improved public transport	0,4	210	−6 870
Increase of charging station EV	0,7	528	554
Increased production of biogas from MSW	30	370	480
Increased recycling of plastics ^b	43	37	48
BECCS ^c	>2000	50	120
Bio coal large ^c	250	<0	?

^aNot valid after peak boiler fuel switching or closure of coal CHP in 2022 (e.g. costs per ton increase).

^bAssumes biogas plant is constructed and refers to additional marginal cost in relation to this option.

^cTotal technical potential. For this paper a scenario 100 kton of CO₂ from bio coal and about 850 kton CO₂ from BECCS is assumed.

the effectiveness of options having negative costs (Levihn, 2016; Taylor, 2012; Ward, 2014).² It is also possible that the difference between private and social costs could lead to both over and under implementation of many of the listed abatement options. For example, the social benefit of improved public transport is greater than what it would cost the city to implement. As a result, less than optimal improvements would be implemented as the positive externality of improved public transport is not reflected in the market price. Furthermore, the cost to the local utility (SE) differs from the cost to the city, although both are private market actors. The cost to the utility was not considered in the WSP screening and is therefore not shown in Table 1. It should be noted that the city is both a customer and an owner (retaining 50% of SE shares).

BECCS has the largest abatement potential and also seems cost effective relative to many other measures currently being considered or implemented. Biochar has the second largest abatement potential, half deriving from storing carbon in the soil and half from estimated additional GHG benefits through soil improvements. Biochar is currently the subject of a business development project, which is why its private costs are listed as less than zero.

3. Methodology

3.1. Techno-economic calculations

To understand the cost of BECCS relative to other abatement options, as well as how BECCS incurs both private and social costs, the techno-economic conditions of the different parts of the BECCS value chain need to be understood. The calculations used as a basis for the present analysis replicate and update the calculations used as input to the WSP/Stockholm municipality report (Bondemark et al., 2018), discussed in the “Background” section of this paper. While the WSP/Stockholm report was not peer reviewed, it is representative of the knowledge possessed by Stockholm City Council.

The calculated costs of transportation and storage are based on a scenario in which a BECCS project in Stockholm utilizes more mature storage sites in Norway. Costs are based on Kjærstad et al.

(2016) and ZEP (2011a) for transport and on ZEP (2011b) for storage. The costs of transport were adapted to the DH case by taking account of the seasonality of transportation needs (i.e. greater need for transportation in winter due to higher heat demand, and thus higher CO₂ production rates). In addition, the costs of utilizing storage in the Baltic Sea (in Faludden aquifer south of the island of Gotland) were also calculated, but with high uncertainty due to the immaturity of such an option.

To uncover the cost of the BECCS process, including its effect on the heat and power output of a plant, data from the SARGAS trials at Värtaverket conducted from 2007 to 2009 were used as input to energy-system-modeling software. The Minerva software is least-cost-planning software taking account of load duration, with distributional boundaries, as well as the interaction between heat and cooling production. Minerva is a considerable improvement over the Optima model used by Levihn (2014) and Levihn et al. (2014) and is today used at SE for investment planning. The calculations on which this paper is based have very high validity for determining the private cost of BECCS investments. Minerva calculates for the 2016–2040 period and includes already decided on changes to the production mix in Stockholm.

To find the corresponding cost of CO₂ capture, the net present value of implementing BECCS was calculated by iteratively changing the cost of CO₂ in Minerva, until NPV = 0 was achieved while accounting for the investment. Thus, the change in merit order due to changed operational conditions was accounted for. The approach allows considering costs related to system effects, which is highly relevant for energy systems with one or few operators such as a DH system. In this case the nature of cost/profit charring between partners in the DH system is accounted for. The downside is a more aggregated representation of costs. What was not included were the dynamics whereby the costs of CO₂ and of European Emission Allowances (EUAs), in particular, have direct impact on the market price of electric power (see e.g. Lund et al., 2013), which should be considered in future versions of the calculations.

While other carbon-capture technologies could be relevant, calculations were based on the HPC process due to familiarity, internal availability of knowledge at SE, and documentation of the SARGAS trials. After the trials, a full-scale design was developed and its cost estimated. While the SARGAS process was designed for pressurized boilers, the flue-gas stream is taken before the gas turbines of the PFBC process. In PFBC, gas turbines are used to drive the compressor pressurizing and fluidizing the bed. As

² For example, the relative economic and abatement potential of the LED streetlight option is better than that of the solar PV option (€96 million and 0.4 kton p.a. for LED vs. €21 million and 0.1 kton p.a. for PV)? See the references for further discussion of the matter.

a result, utilizing HPC on a non-pressurized unit would require work to pressurize flue gases ahead of the absorber, while the work normally lost by reducing pressure over the gas turbines in PFBC is avoided. In the calculations made for this paper, a simplified assumption was made that the results of the SARGAS trials were also valid for non-pressurized boilers with better steam data than the PFBC units steam data. It should be noted that significant factors, such as parts of the flue gas composition of the new KVV8 biomass unit, with state-of-the-art flue-gas cleaning and flue-gas condensation, are more suitable for carbon capture than are the much older coal/biofuel PFBC units.

In contrast to conventional CCS application on power only production in condensing plants, CHP allows for more process integration through heat recovery from different steps in a CO₂ capture process. Not included in this study is the potential to utilize the existing heat pumps at Värtaverket to recover heat down to 4 °C.

3.2. Scenario design

The scenario in this report used one BECCS unit considered for implementation as well as a more modest biochar implementation, both having CO₂ abatement potentials less than the amounts listed in Table 1. It is also assumed that plastic recycling will be in place by 2020, coal will be phased out by 2022, and large-scale biochar will be implemented by 2025. The biochar corresponds to 60 MW of DH capacity and 100 kton of CO₂ reductions p.a. Full-scale BECCS is set to be in place in 2027 and will include the new KVV8 plant, covering 2.5 TWh of present biomass utilization. Therefore, 3.5 TWh of solid biomass and biogenic fractions in MSW remains in the system after this BECCS implementation.

Fuel switching of peak/backup boilers is set to linear reductions towards zero emissions between 2020 and 2030. The other options are either not valid after implementing this scenario or not related to DH. Many other combinations, chronological implementation sequences, and scenarios support a trajectory towards net negative emissions from Stockholm DH and power generation. The design of this particular scenario is based on the feasibility of practical implementation under an aggressive climate change mitigation target.

Calculated CO₂ emissions only take account of direct fuel-related emissions. CO₂ was not allocated in relation to electric power production and consumption (see e.g. discussion in Levihn, 2014)). This was a joint decision by the research team, as such estimates merit attention in a separate paper and do not advance the purpose of the present study.

The calculations of the social cost of BECCS have not been updated, but as the recalculated private cost of BECCS is in the range of that used in previous calculations of the social cost by WSP (Bondemark et al., 2018), it is assumed that the size of the social cost is representative of the analysis performed here.

3.3. Description of the HPC process

In the considered design, the flue gases would be led from the KVV8 biomass CHP unit through an absorber, which is the gas-absorption step in the well-known HPC process. In the absorber column, the flue gas comes in contact with a solvent consisting mainly of hot potassium carbonate, which under increased pressure and temperature absorbs CO₂ and H₂O and forms bicarbonate (HCO₃⁻¹); in the unpressurized desorber column (i.e. the carbonate regeneration step), the bicarbonate reverts back into potassium carbonate, carbon dioxide, and water. The regenerated solvent is recycled back to the absorber after energy recovery. In the next step, the carbon dioxide is compressed and cooled before transport and stationary storage. Any H₂S possibly occurring in

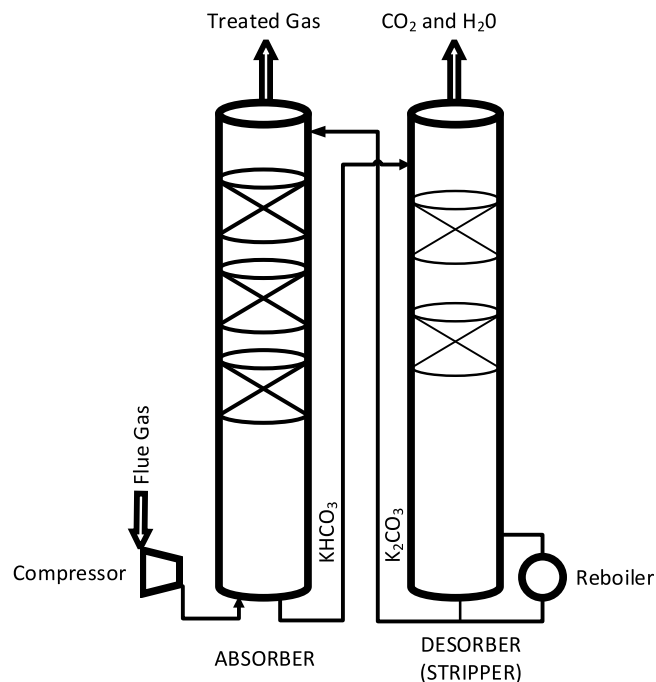
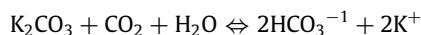


Fig. 2. Schematic of the HPC process.

the flue gas would be absorbed in the absorber, forming bisulfite (HS⁻¹) in the regeneration step (see Fig. 2).

The reactions in the absorber and desorber columns of HPC process are reversible and proceed from left to right in the absorber and from right to left in the desorber:



4. Results

4.1. CO₂ reduction trajectory

In terms of technical capabilities there are few obstacles to implementing NETs in the Stockholm region. Installing BECCS on the KVV8 plant would result in the net removal of about 850 kton of CO₂ p.a., excluding the benefits of renewable power production. The effect of closing the coal/biofuel PFBC unit is more sensitive to fluctuations in the electric power market, and reduces CO₂ emissions by 410–620 kton p.a. (excluding the negative system effect of reduced power production) based on the scenario in this study. The smaller reduction potential from closing the coal/biofuel PFBC unit is mainly attributable to less utilization time. In addition to direct removal of CO₂, the KVV8 plant still would produce over 0.6 TWh of predictable renewable electric power (reduced from 0.8 TWh without BECCS) and 1.8 TWh of DH.

Fig. 3 presents the future scenario for reducing CO₂ emissions including NETs for the whole DH system in Stockholm. In the first years, incremental increases in production from the recently commissioned KVV8 plant reduce emissions from other units behind it in merit order in the system, including the coal/biofuel PFBC unit, which operates fewer and fewer hours. Starting in 2020, the new sorting facility enables a 43 kton reduction in fossil CO₂ from MSW combustion, seen as the reduction of CO₂ between 2019 and 2020. The first big shift down, however, occurs between 2022 and 2023 as the coal PFBC unit is decommissioned. After this, considerable progress could be achieved by commissioning a biochar production unit in 2025. Then, about 200–250 tonnes of net fossil CO₂ remains in the system. The incremental shift

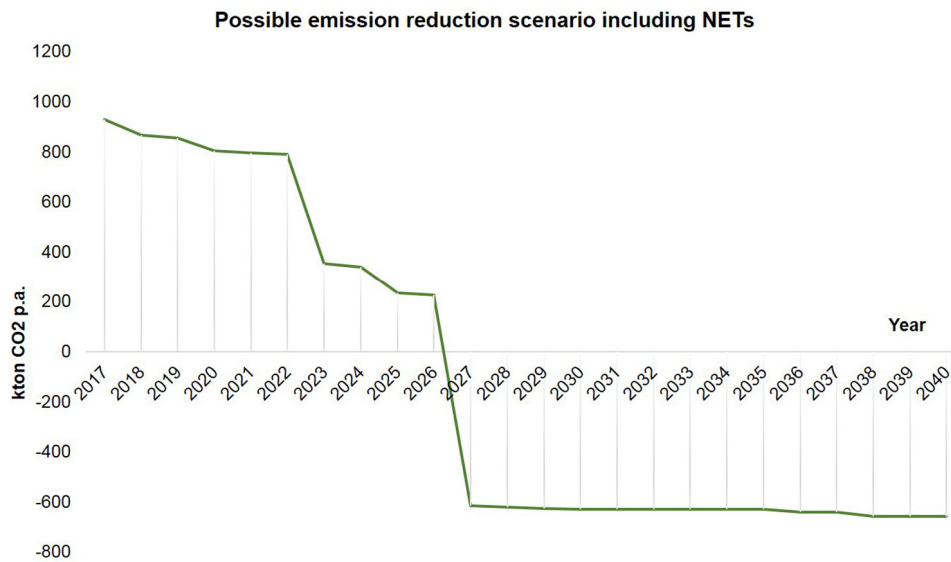


Fig. 3. Scenario for aggressive CO₂ reduction from DH and electric power generation in the Stockholm region.

of replacing 700 MW of fossil-fuel peak and backup boilers with bio-oil units is barely visible.

The major step towards net negative emissions would be implementing a single BECCS unit by retrofitting KVV8. In practice, such a development would shift net CO₂ emissions to about -600 kton p.a. From the calculations and simulations in Minerva, it should be noted that BECCS and biochar do not compete for resources or the availability of storage. Rather, they are complements, as some local biogenic fuel fractions unsuitable for combustion in fluidized beds with advanced steam data (e.g. due to alkali contents) are more suited for slow pyrolysis. This result counters the polarization between abatement options often found in the literature (see e.g. Woolf et al., 2016).

BECCS implemented with CHP could also be well suited for balancing intermittent renewables. A well-designed DH system with CHP and heat storage could shift production between CHP production and heat production only, effectively bypassing the turbines (Levihn, 2017). This would not require changed boiler operation and thus would not affect the flue gas composition or flow. During more extreme operation (in the Nordic countries, a cold winter week with high pressure, little wind, and a dry year with reduced hydro potential), it would be preferable to shut down the CO₂-capture process to favor optimal power production; this possibility could affect the choice of capture process and plant design. Something that requires future R&D attention.

4.2. Techno-economic analysis

The cost analysis of BECCS in the case of Stockholm is clearly divided into four major parts. The first is the capital costs of constructing the HPC scrubbers as well as the compression, storage, and shipping terminal. Capital costs of transport and storage are external to the Stockholm context, which is why they are treated as two bought services. This is close to the actual outlook, as it is highly unlikely that either Stockholm city or SE would construct or operate CO₂ storage or ships themselves. The energy penalty and compression/cooling of CO₂ contribute the most to the cost increases of operating a potential BECCS unit (see Table 2).

The HPC process has advantages and disadvantages compared with other CO₂-capture processes. While it is a well-known post-combustion technology suitable for retrofitting, it does not require expensive and often patented amines. On the other hand, the energy penalty in terms of reduced net power production is

large, so it is unsuitable for condensing power plant applications in which heat cannot be recovered as a usable product. On the other hand DH and CHP applications make the HPC process interesting as electric power is not the only product produced. In the particular case of Stockholm DH, heat recovery from a capture process is further enabled by low return temperatures, which average 41 °C on an annual basis (Levihn, 2017).

Heat recovery from the HPC capturing process has an approximate value of 7 €/tonne CO₂ captured, reducing the capture and liquefaction cost with 17% to 37 €/tonne CO₂. The cost is due to capital expenditure and changed output which affect electric power sales, in part countered through a positive system effect due to increased heat recovery substituting other district heating production in the system. Further process optimization and integration with onsite heat pumps should allow further reductions of the cost. A topic where much more further research is required.

From the results it is evident that the cost of storage and transportation is considerable, constituting 33%–60% of the total cost of BECCS. In calculations of transport costs, an average speed of 12 knots was assumed. CAPEX of ships is assumed to be €46 million per ship. Up to three ships are required during operation. KVV8s utilization time is about 70% per year. For the lower shipping cost, shared infrastructure is assumed where the ships are used by other actors during the summer when district heating demand is low and KVV8 not used. Port fees are assumed to be 2.33 €/per tonne CO₂ and is included in the transport cost. Storage costs are directly extrapolated from costs given in (ZEP, 2011a).

It should be noted that other corporations develops storage and transport infrastructures³ and aim at providing/selling it as a service. Thus private cost of transport and storage is variable from the perspective of Stockholm Exergi. It is also highly likely that initial storage infrastructure will constitute a natural monopoly; as a result, this share of the total cost of BECCS could increase dramatically if a storage infrastructure supplier demands quick large returns on their investment. In total, the cost of BECCS in Stockholm is estimated to be in the region of €55–93/tonne of CO₂, with the largest uncertainties being related to the investment cost of the capture unit and cost of utilizing storage infrastructure. It should be noted that this differs slightly from

³ At the moment a project called Northern Lights supported by Equinor (former Statoil), Shell and Total works on developing storage and transport solutions similar to what is assumed in this report.

Table 2
Cost of BECCS at the KVV8 unit in Stockholm.

INPUT			
Flue gas flow	162.5	kg/s	Based on SARGAS design
Electric power capacity	−37	% of installed capacity	Including capture, compression, and cooling
Heat power capacity	+9	% of installed capacity	Heat recovery from process
Fixed O&M	20	€, millions p.a.	HPC fundamentally lower cost than process using amines
Investment	200	€, millions	Recalculated from SARGAS design
Results			
NPV = 0, EUA equivalent	37	€/tonne CO ₂	Brake-even point for cost-neutral capture
Transport, Norway	17–27	€/tonne CO ₂	Depending on level of shared infrastructure
Storage, Norway	6–23	€/tonne CO ₂	Depending on level of shared infrastructure
<i>Sum</i>	23–50	€/tonne CO ₂	
Transport, Baltic Sea	12–19	€/tonne CO ₂	Depending on level of shared infrastructure
Storage, Baltic Sea	6–23	€/tonne CO ₂	Depending on level of shared infrastructure
<i>Sum</i>	18–42	€/tonne CO ₂	
TOTAL COSTS			
Norway, high	93	€/tonne CO ₂	
Norway, low	60	€/tonne CO ₂	
Sweden, high	79	€/tonne CO ₂	
Sweden, low	55	€/tonne CO ₂	

the earlier cost estimates in the climate action plan of Stockholm municipality, as shown in Table 1.

While renewables and other low-CO₂-emitting technologies (including nuclear power) could become more competitive as a result of economic policy targeting reduced fossil energy consumption, such policy could also decrease the incentive for BECCS development. In the Nordic electric power system, techno-economic boundaries (e.g. market legislation, electric transmission between nations, installed capacity, and marginal cost pricing) result in fossil-fuel production often setting the market price for electric power generation (Lund et al., 2013). Increased EUA prices under the European Emission Trading Scheme (EU ETS) could therefore increase the financial return of low-CO₂ electric generation. As a result, the alternative cost due to the efficiency penalty from the reduced power output of a BECCS plant compared with a regular biofuel CHP plant increases with the level of EUAs, reducing the incentive for BECCS. Including BECCS in the EU ETS by obtaining EUAs for stored biogenic CO₂ would partly counter this.

The cost estimation also assumes base-load operation of the unit. While CHP plants can allow flexible electric power generation without changing the load of the boiler if combined with thermal storage, the considerable energy penalty for electric power production is potentially economically challenging if part time BECCS-bypass is not allowed. A result from this study is that during the highest-priced hours, there are incentives to temporarily bypass the capture unit and favor full electric output. Low or negative power price hours, on the contrary, could allow more or less free CO₂ capture, compression, and cooling. The flexible management of BECCS therefore has potential to reduce the cost of captured CO₂. This is contrary to research such as that of Bhave et al. (2017), in which BECCS is assumed to be base-load production, and should be the focus of future research.

4.3. Putting BECCS into perspective

The cost interval of €55–93/tonne of CO₂ is the private cost to the utility SE. Stockholm municipality, which owns half of SE stock, would share increased profits or losses with the other major shareholder, the Fortum Group. As a result, the private cost to Stockholm municipality is half of the private cost to SE, i.e. €23–47/tonne of CO₂. The social cost based on (Bondemark et al., 2018) is €120/tonne of CO₂. In comparison, the cost of BECCS is in range of the Swedish tax on fossil CO₂ emissions, which is above €110/tonne of CO₂, illustrating how Swedish society already values CO₂ emission reductions.

Two options for reducing CO₂ emissions are particularly interesting in this context. Setting stricter energy performance standards only requires administration from the city, which is why it is a cheap option relative to the corresponding private cost. For society, increasing the cost of building construction could have large consequences, which is why it is very risky for the municipality to set stricter than optimal standards. Similarly, governmental subsidies for installing PV energy strongly incentivize private actors to invest far more than the social cost optimally requires, basically resulting in a government-induced market failure. Both these options also have a very marginal effect on reducing CO₂ emissions.

Large improvements in the energy performance of old buildings also have a large social cost, but here the private cost to the municipality is also large, dampening the incentive for implementation. Minor improvements could be economical, though. Still, both retrofitting existing buildings as well as setting stringent energy performance standards have negligible effects on CO₂ emissions after the coal plant is closed in 2022 and the peak/reserve boilers are converted to biofuels. As a result, the cost of energy efficiency in terms of €/tonne of CO₂ emissions would approach infinity as the targeted emissions approach zero.

The results of (Bondemark et al., 2018) suggest that the difference between the social and private costs of improving public transport will lead to less than optimal implementation. It is interesting to note that BECCS is more techno-economically efficient from a social perspective than either increasing the number of electric vehicle charging stations or increasing biogas production. These measures are much cheaper for the municipality, though, so currently these two options are apparently on the way to being implemented.

So why is not more attention paid to BECCS? Part of the answer lies in its being such a good way (technically) to reduce CO₂ emissions. Even though the cost per tonne of CO₂ is relatively low, the total cost per year will grow with the amount of CO₂ abated. Implementing BECCS might become too great an economic burden for private actors than is feasibly managed in practice.

For SE, abating 850 kt of CO₂ p.a. would in practice cost €47–79 million p.a. In comparison, SE's annual turnover is around €700 million, so income would have to increase by 10% to accommodate BECCS implementation in one CHP plant. In 2016, SE's profit was about €120 million, so implementing a single BECCS system would have reduced profits by 39%–66%. At the same time, closing the coal unit and replacing other old and

unreliable units in the system requires € billion range investments. As a result, even though BECCS is comparatively efficient in terms of techno-economic performance, developing a single unit would still entail a high private cost relative to other needed investments.

As a result, it is highly unlikely that investments will be made before supporting economic factors are in place (e.g. policies, business models, and demand). In this sense, investments in technologies with smaller abatement potential are easier: they can be made as image enhancers, and their risk is lower in uncertain policy regimes. As such, clear political commitment or customer demand is required to provide long-term price signals if BECCS is to be implemented.

4.4. Policy implications

Several policy-related challenges are related to successful BECCS implementation in Stockholm. Besides the obvious lack of internalization of the negative effects of CO₂ emissions, one of the externalities discussed by Krahé et al. (2013) is of specific interest.

While capabilities for biomass sourcing (avoiding challenges discussed in e.g. Tokimatsu et al., 2017), CO₂ capture, and transport contracting are readily available, storage is external to the context of Stockholm. As discussed earlier in this report, the best short-term alternative seems to be ship transport for storage in Norway. Thus there would be inter-firm dependence and potentially international dependence as well. If Sweden successfully implemented policy instruments supporting BECCS, they would depend in the short term on Norway also supporting BECCS or CCS. Likewise, Norwegian construction of enough storage capacity for international delivery of CO₂ would depend on Sweden or other nations implementing policy instruments supporting the delivery of CO₂ to be stored. There is clearly a need for international cooperation to coordinate policy instruments, in order to target cross-sectoral market failures. It must also be noted that the prospect of being dependent on a potential monopolist, and thus subject to imperfect competition, for the supply of storage infrastructure also increases the economic risk of implementing BECCS in Stockholm.

5. Conclusion

While BECCS seems both necessary to reach global climate change abatement targets and relatively efficient compared with other climate change abatement possibilities, many barriers to large-scale implementation exist. This paper has discussed the potential for implementing BECCS through the HPC process on CHP plants in Stockholm. This case is interesting as the required technical capabilities, for example, as discussed by Mander et al. (2017), are in place. Currently, 6 TWh of the fuel used has biogenic origins, mainly derived from woodchips based on forest residues and the biogenic fraction of MSW. Furthermore, there is local experience of operating the HPC process with hot potassium carbonate at a previous gas refinery, as well as pilot tests of CCS on a CHP plant. Concerning storage, much infrastructure is already in place, being planned, or under consideration in neighboring Norway.

The calculations and results presented in this paper has demonstrated the relevance of including CHP applications, and the HPC process on CHPs in particular, on different research agendas. Provided the urgency of deploying NETs according to SR 15 (IPCC, 2018) and the potential contribution of MSW and biomass CHP applications in district heating, it is suggested that NETs and BECCS are introduced to the 4GDH framework. Required research range from process integration and waste heat recovery

from different capture processes, to the interplay of such processes on multi energy management issues (e.g. flexibility relative intermittent renewables).

In Stockholm, one NET is in place today in the form of a biochar unit supplying DH to the regular network in Stockholm. This biochar plant is not the focus of this paper, but it is worth noting that in Stockholm, BECCS and biochar do not cannibalize, but rather complement each other. In practice, many biofuel resources unsuitable for large-scale combustion (due to alkali contents or other factors) are suitable for use in pyrolysis processes. The effects of biochar in terms of soil improvement and direct storage of CO₂ are also differentiated.

While BECCS seems comparable in techno-economic efficiency to other means of reducing CO₂ emissions in Stockholm, the technology is in a way too good. In practice, implementing BECCS on a single CHP plant would result in enough negative emissions to make the actual cost (even though the process is relatively cost effective) too high for the utility SE. In this case, a single implementation potentially costs about 10% of SE turnover and reduces profit by up to 66%. This poses an interesting barrier, in practice reducing the willingness to invest in technologies with large-scale benefits and CO₂ abatement potential, as the corresponding economic risk posed by policy uncertainty and market volatility increase with the amount of CO₂ abated. As discount rates normally follow risk, policy makers will either need to make long-term commitments or allow a higher margin on supporting policy.

Near-term implementation necessitates, in addition to the inter-firm relationships discussed by Krahé et al. (2013), the international coordination of policy. In this particular case, near-term storage is determined to be most feasible in Norway, requiring ship transport from Stockholm. Firms such as SE would thus depend on both Swedish and Norwegian policy, as well as on a potential monopoly in storage infrastructure. As the Nordic region has a history of close relationships and policy coordination (actively or by accident), this does not seem too high a mountain to climb.

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