MISTRA
THE FOUNDATION FOR STRATEGIC ENVIRONMENTAL RESEARCH

Gamla Brogatan 36–38
111 20 Stockholm, Sweden
Telephone +46 8 791 10 20
Fax +46 8 791 10 29
mail@mistra.org
www.mistra.org

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Prestudy of BECCS

Bio-Energy with Carbon Capture and Storage

This is a pre-study of the BECCS technology which aims to:

- investigate and document ongoing international research
- summarize the current scientific understanding
- describe and propose research questions for further studies

The pre-study was funded by Mistra and written by Dr Michael Obersteiner, Austria, assisted by Henrik Karlsson Biorecro AB, Sweden. The authors themselves are responsible for the content and conclusions of the pre-study.

Pre-study of BECCS

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Executive Summary

BECCS (Bio-Energy with Carbon Capture and Storage) is a technology aiming to mitigate climate change by the combination of bio-energy carbon dioxide sources with carbon capture and storage. The global potential for BECCS is estimated to be very large, however, there is no comprehensive overview of the field and existing knowledge about BECCS systems has to date had a limited diffusion outside the scientific community.

This is a pre-study of the BECCS technology which aims to (i) investigate and document ongoing international research, (ii) summarize the current scientific understanding, and (iii) describe and propose research questions for further studies.

A key result of the research undertaken so far is that BECCS systems can produce large scale negative carbon dioxide (CO_2) emissions at the gigaton scale. While the efficiency and cost at which these negative emissions can be achieved varies with the design, scaling and implementation of the underlying biomass and CCS systems, BECCS compares favourably to most other climate mitigation measures. Many of the more ambitious climate mitigation targets may be unattainable without BECCS, but feasible with BECCS. For less stringent targets, BECCS may significantly reduce the cost and timing of overall mitigation. To make these important insights functional, a better understanding about the obstacles and opportunities for BECCS deployment in specific economic, technical and political contexts is needed.

The study concludes that while research into BECCS is growing steadily, there is less than optimal coordination between the actors in the field. One apparent reason is the complexity of the issue and its true inter-disciplinarity nature. Another reason could be the hitherto lack of research funding dedicated specifically to the study of BECCS, implying that current knowledge about the technology has been developed as part of research in related areas, rather than as a concerted effort.

Drawing on these conclusions, this study highlights several areas in which more work is necessary and where Mistra could play a role. Notably, the study identifies a need for (i) coordination and further dissemination of knowledge on BECCS to a variety of stakeholders, (ii) further research on BECCS deployment, preferably with a systemic perspective, and (iii) real projects to generate learning-by-doing and evidence-based input data.

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1. Background and aim of study

1.1 Mistra specification and study aims

CCS (Carbon Capture and Storage) is a technology aiming to mitigate climate change, today mostly connected to carbon dioxide emissions from fossil fuels. Ongoing research is immense. However, relatively little research has been undertaken in the area of combining bio-energy sources such as biomass fuelled power plants, pulp mills or bio-fuel production plants with CCS in so called BECCS systems (Bio-Energy with Carbon Capture and Storage). At the same time, the global potential for BECCS is estimated to be very large.

This is a pre-study of the BECCS technology which aims to:

- investigate and document ongoing international research
- summarize the current scientific understanding
- describe and propose research questions for further studies

1.2 Author and acknowledgements

The study was commissioned by Swedish research fund MISTRA in conjunction with its ongoing projects on CCS (www.ccs-politics.se) and forestry research (www.futureforests.se). It was undertaken by Michael Obersteiner (International Institute for Applied Systems Analysis, IIASA, Austria) with assistance from Henrik Karlsson (Biorecro AB, Sweden). The study builds on a comprehensive database of BECCS-related publications collated by the authors, which has been assembled with the assistance of Ariff Munshi and Hui Qi Foong (National University of Singapore, NUS, Singapore).

We wish to extend a thank you to the following researchers who contributed with input for the database and this study: Christian Azar, David Barnes, Martin Dubois, Maria Grahn, Stefan Grönkvist, Anna Krohwinkel Karlsson, Haroon Kheshgi, Eric Larson, Christopher J Lehmann, Fredrik Normann, Stephen Pacala, Simon Shackley, Steve Smith and Paul Upham.

2. The setting of BECCS

2.1 Climate change mitigation

Since the onset of the industrial revolution, the levels of greenhouse gases (GHGs) in the earth's atmosphere have risen dramatically. The atmospheric concentration level of the dominant GHG, carbon dioxide (CO_2), has risen from below 280 parts per million (ppm) to over 390 ppm in the last two hundred years. CO_2 concentration levels are increasing at accelerating speed because of growing emissions of CO_2. The main reasons are the combustion of fossil fuels such as coal, oil and natural gas, as well as changes in land use, such as forest logging. This has led to a 0.8 degree Celsius increase in global mean temperatures over the past two centuries. If this trend is not broken, the global mean temperatures are expected to surge with between 1.8 to 4.0 degrees Celsius because of additional emissions during the 21st century. This would in turn have dramatic negative effects on global ecosystems as well as the global economy.[1]

The need to stop the trend of climate change has led to intensive research activity on different mitigation options, as well as political discussion and negotiation about how the cost for these options should be divided among countries, industries and individuals. Among these options, both bio-energy as well as carbon capture and storage (CCS) have been heavily evaluated and there are many research and development activities in these two fields.

One option that has been considered to a lesser extent is the possible combination of these two technologies into systems of Bio-Energy with Carbon Capture and Storage (BECCS). The relatively small, yet highly relevant body of existing research and knowledge about BECCS systems has to date had a limited diffusion outside the scientific community. The focus of this study has been to collect, compare and summarize available studies on BECCS in order to give an overview of the current scientific understanding within the area.

2.2 BECCS in climate change mitigation

Most GHG emission mitigation options are centred on moving energy and economic systems from a high carbon emission pathway to a low or zero emission alternative. This involves increasing efficiency and switching to less or zero emitting fuelling alternatives such as wind, hydro, biomass and solar energy. There are also possibilities to enhance natural CO_2 sinks through afforestation and reforestation, even though the potential and effectiveness for these options are limited over time, especially considering the large and increasing amount of fossil fuel emissions.

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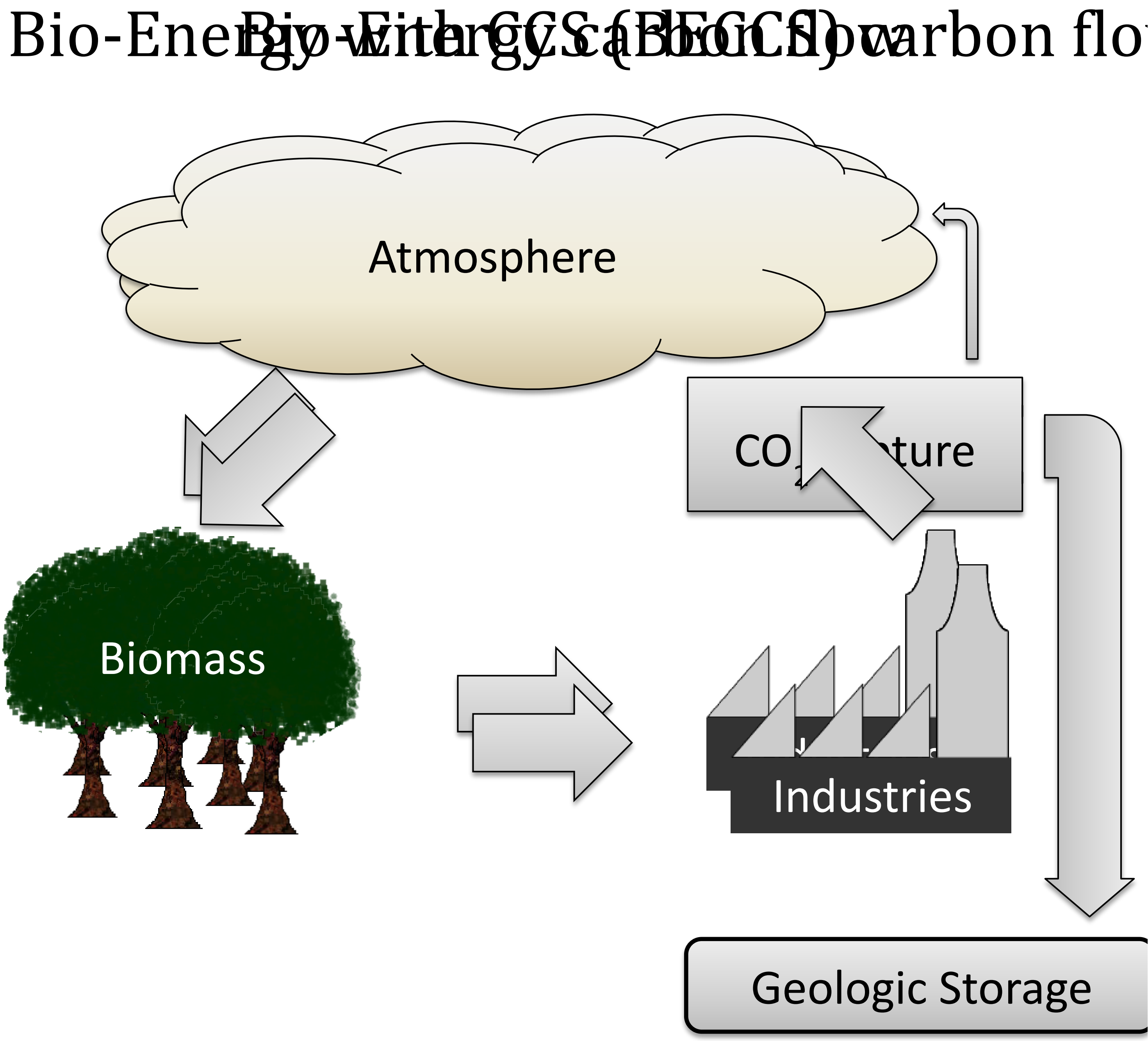
[1] IPCC 4th Assessment Report, Solomon et al., 2007

The combination of biomass with CCS in BECCS systems involves creating permanent CO_2 sinks at considerable scale, while at the same time providing bio-energy to replace fossil fuels. Since biomass extracts CO_2 from the atmosphere during its growth, storing this geologically results in net removal of CO_2 from the atmosphere. The process is the opposite to that of fossil fuel emissions, by which CO_2 is



added to the atmosphere. Thus, BECCS is said to create *negative* CO_2 emissions, see figures 1 and 2.

Figures 1 and 2.

BECCS can be applied on a wide range of biotic CO_2 sources, such as biomass combustion power plants combined heat and power plants, in biofuel production of ethanol and biogas, in various processed in pulp and paper mills and in combination with emerging technologies such as gasification of biomass of Fischer-Tropsch conversion facilities. However, there are very few projects in development presently, especially in relation to the vast short and long term potentials of this technology to combat global warming.[2]

According to the IEA (Interantional Energy Agency), an optimal portfolio of mitigation technologies to meet the 450 ppm target includes no less than 2.4 billion tonnes of BECCS in 2050. To be able to reach there, efforts would need to start now. Already by 2020, more than 35 million tonnes of BECCS annually needs to be in place in the IEA roadmap. [3]

Some countries have a larger potential for BECCS than others, becaue of large scale biomass facilities. Examples of such countries are Brazil, Sweden and Canada. In a report from the Swedish company Biorecro, it was shown that BECCS has the largest potential of all single mitigation options for Sweden at more than 27 million tonnes annually. This was compared to the total emissions from the Swedish transport sector, which has about 21 million tonnes of emissions per year, including all cars, trucks, trains, planes and boats.[4]

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[2] Karlsson et al, 2011
[3] IEA, 2009
[4] Karlsson et al, 2010

3. Current status of the study of BECCS

3.1 First mentions

The concept of combining CCS with biomass was first mentioned by Robert H. Williams in the working paper “Fuel Decarbonisation for Fuel Cell Applications and Sequestration of the Separated CO_2”, published in January 1996 by the Centre for Energy and Environmental Studies at Princeton University.[5] In the paper, Williams not only mentioned the combination of CCS and biomass as a viable carbon dioxide emission mitigation alternative, but also the possibility to attain negative CO_2 emissions. The paper suggested that one possible use of these negative emissions could be to offset emissions arising in countries which do not want or are not able to sufficiently decrease their CO_2 emissions.

The working paper by Williams was cited by Herzog and Drake the same year (1996) in the first peer-reviewed mention in the publication Annual Review of Energy and the Environment.[6] After that, no other articles on BECCS appeared until the beginning of the new millennium. In 2001, BECCS had its first mention in a wider audience publication through the article “Managing climate risk” by Obersteiner et al., where BECCS was pointed out as a dynamic tool to confront the challenges posed by incoherent policy action and uncertainties in climate scenario modelling.[7] Thus, in these very first articles, the main aspects of BECCS found to date were already exploited, even though the understanding of the subject has deepened since.

3.2 Number of published articles

Since the first mention in 1996, this study has found 67 articles published in peer-reviewed journals which touch upon the concept of BECCS. Of these 67 articles, 41 analyze the BECCS technology as a part of or as the main focus of the article. The other 26 only mention BECCS briefly, often as part of a listing of mitigation options.

In addition to the 67 peer-reviewed articles, an additional 36 articles published in other types of outlets were found. These articles typically appear in conference proceeding volumes, but since they are not peer reviewed they have a variable quality and are not included in this review.

It is interesting to look at the overall frequency of published articles. The diagram below displays the number of articles published each year along with the weighted moving average over two years. As can

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[5] Williams, 1996
[6] Herzog et al., 1996
[7] Obersteiner et al., 2001

be seen, there was very little publication activity after the first mention in 1996, but since the start of the new millennium, there has been a steady increase in the level of research in the field, see figure 3. Still, there are very few articles about BECCS compared to other areas in the climate change portfolio such as solar power or, indeed, the separate areas of biomass energy and that of CCS.

The articles appear in both climate scenario modelling, biomass as well as CCS related publications such as Climatic Change (10 articles), Energy (8 articles), Mitigation and Adaptation Strategies for Global Change (6 articles), Biomass and Bio-energy (5 articles), but also in general publications such as Science (5 articles) and publications focusing on somewhat different areas, e.g. Technology forecasting and social change (1 article) and Computational Management Science (1 article). In total, the 67 articles were published in 25 different publications.

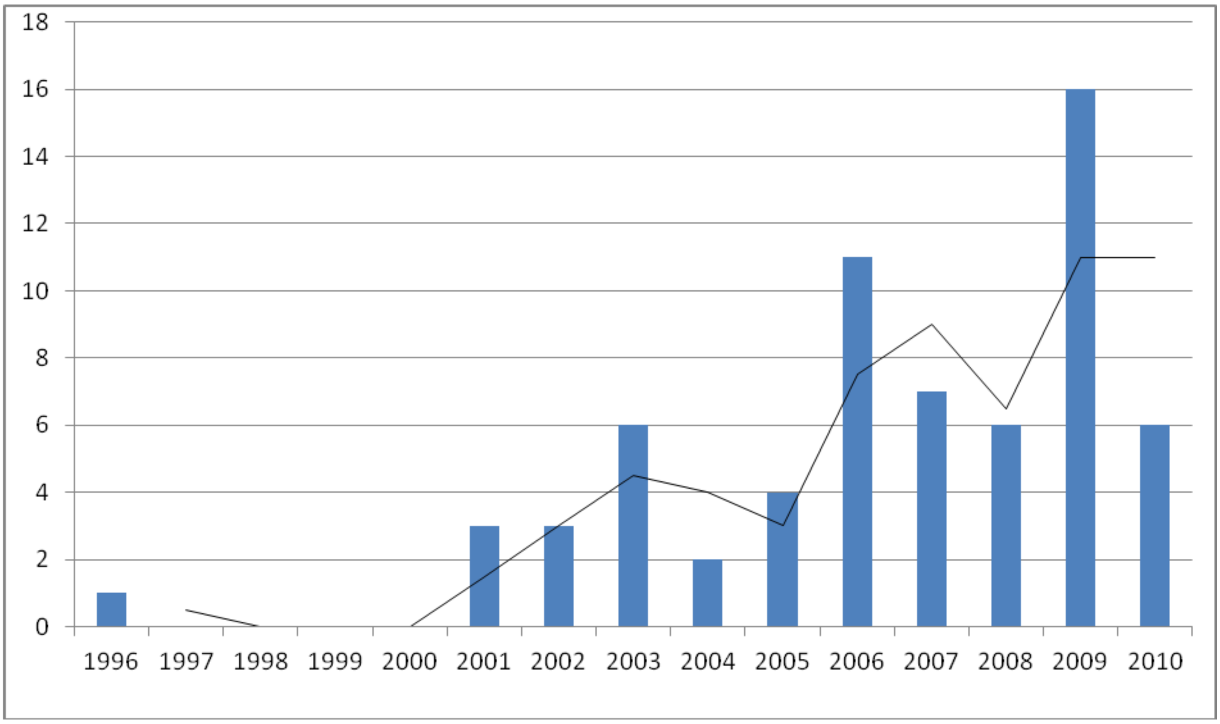

Figure 3. Level of publishing activity of BECCS articles since first peer reviewed publication in 1996, black line indicates bi-annual mean value.

3.3 Coordination of research

It is interesting to note the wide array of ways in which BECCS has been denoted. The term “BECCS” (Bio-Energy with Carbon Capture and Storage) was first used in the IPCC 4th Assessment Report in 2007.[8]

[8] Fisher et al., 2007

This has lately become more and more an accepted term,[9] but there are still many other denotations for the concept such as "BECS",[10] "biomass-based CCS",[11] "BCCS",[12] and "biotic CCS". The previous and to a large extent ongoing terminology sprawl makes it considerably more difficult to assess and follow research in the field, as keyword searches tend to give little feedback when authors use different terminology.

One result of the lack of a common reference point is that article authors tend to cite each other only to a limited extent, and are probably unaware of each other in most cases. This fact has been corroborated by the researchers who have written the articles in the database. There are though a couple of knowledge clusters where researchers have interacted and frequently refer to each other's work. These centres have also in some cases interacted and built upon each other's research. Such centres are Chalmers University of Technology, International Institute for Applied Systems Analysis IIASA, Massey University, Netherlands Environmental Assessment Agency PBL, Potsdam Centre for Climate Impact Research PIK, Princeton University, Royal Institute of Technology KTH and University of Calgary.

One apparent reason for why there is less than optimal coordination between researchers is that the field is relatively new. Another important obstacle to coordination, but also a possibility for interesting research, is that BECCS is a truly cross-disciplinary subject. One proof of this is the relatively large number of publications (25 publications for only 67 articles) and the difference in analytical frameworks used in the articles. This implies many different starting points for BECCS-related research as well as several possible directions of research.

3.4 Directions of research

It is of importance to note the different directions of research into BECCS and the various angles from which the BECCS option has been considered so far. There is a large number of directions in the research on BECCS, reflecting the complexity of the issue, and its cross-disciplinary nature. Because of this, there are also some areas which are largely uncovered in the articles published so far (see section on research gaps below).

The main directions indentified in this review are (note that some articles cover more than one of the areas listed below):

A. BECCS as a negative emission opportunity in long term (100 years+) climate mitigation scenarios, [13]

    a. to decrease overall societal costs of meeting various GHG concentration targets [14]

[9] e.g. Azar et al., 2010,
[10] e.g. Royal Society, 2009; Azar et al., 2006; Metz et al., 2005 (IPCC Special Report on CCS)
[11] e.g. Metz et al., 2005
[12] Bonijoly et al., 2009
[13] Riahi et al., 2007, van Vuuren et al., 2007

b. to increase the possibilities of meeting various concentration targets as well as temperature and climate change impact targets [15]

c. to manage the risks associated with [16]

i. uncertainties in long term climate scenario modelling [17]

ii. non-linear climate system reactions (including abrupt climate change and the risks of crossing system tipping points) [18]

iii. late and/or diverse policy action on climate change mitigation [19]

B. BECCS in long term modelling of biomass use and availability, with emphasis on the competition between energy, biodiversity, food, water use, sequestration in soils and standing biomass as well as other aspects. [20]

C. BECCS as part of fossil fuel CCS with co-firing of biomass, [21]

a. to decrease the GHG emissions of the system, and/or [22]

b. to decrease costs and technological difficulties of fossil fuels with CCS [23]

D. Life Cycle Analyses (LCAs), accounting and cost implications for BECCS systems

a. in relation to biomass systems, especially biofuel production [24]

b. in relation to fossil fuel CCS systems [25]

c. in relation to other mitigation options [26]

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[14] Azar et al., 2006, Azar et al., 2010
[15] Clarke et al., 2009, Edenhofer et al., 2010, Fisher et al., 2007 (IPCC 4th Ass. Report), van Vuuren et al., 2010(a)
[16] Obersteiner et al., 2001
[17] Hare et al., 2006
[18] Keith, 2009, Read et al., 2005, Read, 2006, Read, 2008
[19] Krey er al., 2009, Kypreos, 2008, Loulou et al., 2009
[20] Edmonds, 2004, Keith, 2001, Kraxner et al., 2003, Luckow et al., 2010, Marland et al., 2008, Moreira, 2006, Popp et al., 2010, Rhodes eet al., 2008, Sagar et al., 2007, van Vuuren et al., 2010(b), Wise et al., 2009
[21] Haszeldine, 2009
[22] Faaij, 2006
[23] Normann et al., 2009
[24] Campbell et al., 2009, Gibbins et al., 2007, Grahn et al., 2009, Keith et al., 2002, Lindfeldt et al., 2008, Mathews, 2007
[25] Grönkvist et al., 2006 (Mitigation and Adaptation Strategies for Global Change), Gustavsson et al., 2003, Smekens et al., 2006, Squire et al., 2009, van Vliet et al., 2009

E. Techno-economic analyses of BECCS system integration

  a. into existing biomass infrastructure such as pulp mills [27]

  b. into future next-generation technologies such as gasification systems [28]

F. Social and societal impacts of BECCS as a new technology option [29]

3.5 Results so far

A key result of the research undertaken so far is that BECCS systems can produce large scale negative CO_2 emissions. It is also established that the size of these negative emissions varies greatly according to how the biomass is sourced, which type of biomass energy or material conversion system that is used (i.e. pulp mill or bio-energy combined heat and power plant), the permanence of the geological CO_2 storage, how and with which scope the LCA assessment is carried out, and a number of other factors. It has also been found that these negative emissions are difficult and costly to achieve by means of other measures alone, such as direct air capture (because of costs) and forest management (because of scarcity of land and CO_2 retention permanence).

A key finding, which can be considered as a strategic insight for the entire climate change mitigation discussion, is that many of the more ambitious temperature and GHG concentration mitigation targets are unattainable without BECCS, but feasible with BECCS.[30] As such, BECCS is a key technology that yields opportunities which other options (such as wind and solar energy and energy efficiency) do not offer.

The costs of BECCS systems have not been analyzed by a sufficient number of studies to enable a uniform cost perspective. Though, it has been found that the costs of BECCS vary significantly according to where and with what biomass technology BECCS is implemented. Applications to combustion systems typically render higher costs per tonne of CO_2 (with higher costs for first of a kind systems), whereas gasification and fermentation systems have significantly lower costs per tonne. Thus, another key finding is that the economic feasibility of BECCS implementation is decided by how biomass systems are designed, scaled and implemented.

A finding which is interesting and somewhat complex is that BECCS is an option which in a number of cases is cheaper and has a higher mitigation impact per cost unit and biomass input than the mere use

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[26] Johansson, 2009, Keith et al., 2006, Pielke, 2009, Read, 2002, Rhodes et al., 2003

[27] Grönkvist et al., 2006 (Energy), Hektor et al., 2007, Hektor et al., 2009, Kheshgi et al., 2005, Möllersten et al., 2003, Möllersten et al., 2003, Möllersten et al., 2004, Möllersten et al., 2006

[28] Cormos, 2009, Herzog et al., 1996, Rhodes et al., 2005, Schmidt et al., 2010, Uddin et al., 2007, van Vliet et al., 2009, van Vliet et al., 2010

[29] Shackley et al., 2009

[30] E.g. Clarke et al., 2009, Edenhofer et al., 2010 and Fisher et al., 2007 (IPCC 4th Ass. Report)

of biomass energy. That is, BECCS reduces the cost for biomass mitigation per unit of biomass input and also the costs for such mitigation as measured in cost per tonne.[31] This implies that BECCS should be installed in all cases where mitigation cost efficiency and optimal biomass use is desirable. However, more research is needed especially in relation to different biomass systems for this conclusion to become able to generalize.

3.6 Ongoing research and analysis

It should be noted that BECCS during the last two years has started to be included in climate change mitigation and energy technology roadmaps, most notably by the International Energy Agency IEA in their roadmaps for CCS deployment since 2009.[32] There has also been published a national roadmap for BECCS deployment by the Swedish company Biorecro, describing the opportunities of the BECCS technology for meeting Swedish climate mitigation targets.[33]

Currently, the Paris office of the IEA is pursuing work in BECCS. There is also a study under preparation by Ecofys in the Netherlands for the separate entity the IEA GreenHouseGas R&D Programme to assess the global potential for BECCS.

As part of their work on Geo-engineering, the Royal Society in the United Kingdom has briefly assessed the BECCS technology. It could be noted that BECCS turned out to be one of the earliest, least costly and most environmentally sound technologies found in the study by the Royal Society.[34]

There was a session on BECCS and a panel discussion on negative emissions in the latest international major CCS industry event workshop GHGT-10 in Amsterdam, the Netherlands, in the fall of 2010.

The 1st International Workshop on Biomass and Carbon Capture and Storage (dedicated specifically to the topic of BECCS) was held in the fall of 2010 in Orléans, France. It was co-organized by the University of Orléans, Laboratoire d'Economie d'Orléans, Norwegian environmental NGO Bellona and BRGM (the French geological survey). It collected about 40 attendees from mainly European academy, industry and NGOs.[35]

Thus, BECCS is considered more frequently now than only three years ago. Still, this study has found no dedicated research centres, funding, professor chairs or other resources devoted to BECCS specific research. Rather, the research done to date has been carried out in the context of other research efforts.

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[31] E.g. Edmonds, 2004, Lindfeldt et al., 2008
[32] IEA, 2009
[33] Karlsson et al, 2010
[34] Royal Society, 2009
[35] More information can be found at www.univ-orleans.fr/leo/bccs/program.php

4 Future BECCS studies

4.1 Demand for research in published articles

One conclusion which is drawn in a number of the articles is that the BECCS field needs more study and attention.[36] Notably, the contribution of the 3rd Working Group to the latest Assessment Report by the IPCC in 2007 pointed out that "to date, detailed analyses of large-scale biomass conversion with CO_2 capture and storage is scarce. As a result, current integrated assessment BECCS scenarios are based on a limited and uncertain understanding of the technology."[37]

4.2 Research gaps

Drawing from the identified directions of research, some areas seem to have been less, or not at all, covered by the articles found in this study. There are none or few articles covering the following directions:

A. Analyses of actual planned or operational BECCS facilities,[38]

B. Deployment plans or detailed roadmaps for BECCS, outlining the possible expansion of BECCS in the short term until the years 2020 and 2030 (other than interpolated global top-down models),

C. Analyses of the complex interaction between biomass and CCS systems, including specific recommendations on how biomass and CCS systems should be constructed and scaled in order to facilitate for BECCS,[39]

D. National and regional BECCS deployment analyses,

E. Detailed analyses of BECCS in emission trading, carbon tax and other incentive mechanisms,[40]

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[36] E.g. Fisher et al., 2007 (IPCC 4th Ass. Report),
[37] Fisher et al, 2007
[38] There are though a number of non-peer reviewed papers, such as Bonijoly et al., 2010
[39] Even though articles such as Uddin et al., 2007 and van Vliet et al., 2009, compare different gasification systems and identify potential preferred technology options, more information will be required for decision makers to invest on the basis of findings such as these

F. Policy analyses and recommendations for optimal BECCS deployment considering the large amount of constraints such as costs, biomass availability, land use, CO_2 storage opportunities, etc.

The lack of coverage of the above areas can be considered a major gap in the understanding of BECCS, and is also an explanation for the low level of activity in industry and public policy.

4.3 Potential directions and questions for future research

Considering the vast amount of potential directions for future research, and the scarcity of resources at hand for Mistra and other funders, this section will look into what areas that best match the overall strategic goals of Mistra, how future research should be designed to meet these goals in the most efficient manner.

A. One area that needs immediate attention is the **construction of BECCS facilities and the analysis of these** projects. Similar studies of fossil fuel CCS projects have proven to be important references for the academic field of CCS, as well as providing directions for policy and industry decision makers.

    a. Pilot and demonstration projects for BECCS needs to be facilitated, with funding for both planning, construction and operation of small, medium and large scale facilities storing between 10.000 to 1.000.000 million tonnes of CO_2 per year. Such facilities would give a much needed experience of real world costs, technical knowhow and would serve as platforms and data input for further studies.

    b. If funding is too limited for full scale pilots and demonstrations, planning and FEED studies should be facilitated to enable future construction and operations.

    c. Studies associated with these facilities such as LCA assessments, incentive mechanism functionality and optimization, technical optimization studies, etc.

    d. Integration of BECCS with fossil fuel CCS deployment. There are biomass facilities which operate in areas where CCS deployment is planned. The integration of BECCS facilities into the transport and storage infrastructure of these systems would greatly reduce cost and complexity for early BECCS demonstration and deployment. This also includes the co-firing of biomass and fossil fuels, where the integration would be already in the fuel input stage.

[40] Exceptions being Möllersten, 2001, Read, 2002 and Read 2006. This is though a complex area with considerable incongruencies presently

In sum, this area calls for funding towards installations and demonstration rather than exploring theoretical research questions. Though, such demonstrations will be vital for all other studies carried out and for answering real life questions about costs, technological options, scalability as well as regulatory and incentive system obstacles.

B. Detailed **Life Cycle Assessments of BECCS**. In the literature, there is a wide range of LCA estimates for BECCS, but few detailed bottom-up analyses of the LCA impacts of BECCS.

   a. There is a need to establish LCAs for the various systems to which BECCS can be added, such as pulp plants, biofuel production, biomass power and heat facilities. These LCAs need to take into account not only carbon balances but also indirect feedback (if any) to biomass use, water use, other energy use, etc.

   b. There is a need to establish LCAs for future more advanced biomass systems, such as gasification with BECCS, with the same rigor.

   c. It needs to be clearly understood how BECCS affects the need for biomass use, considering the limited availability of biomass and the potential biomass demand feedback of costs and profits from BECCS deployment. Some studies suggest that BECCS deployment will increase the demand for biomass, whereas other state that the increased mitigation potential of biomass with BECCS added will decrease the need for biomass in the energy system.

Relevant research actions and questions are:

- How to best calculate LCA for BECCS systems?
- How should aspects such as long term storage integrity, indirect land use change and emissions from coal mining in co-firing BECCS systems be treated?
- What should the division of the emission accounting burden for electricity, fuels, negative emissions, co-products etc be in a combined multi-output BECCS system?

C. Further assessment is needed of the **interplay between BECCS, biomass and CCS**. Detailed analyses are needed of how biomass supply, transport and use can be modified to facilitate BECCS deployment, and how CCS deployment could be modified to better accommodate BECCS.

   a. Biomass systems are typically small scale, whereas CCS systems benefit from large scale cost efficiencies. The balance between these factors is largely unexplored.

b. Preliminary studies have found that gasification and fermentation are two low cost options for BECCS deployment. It will need more study to assess where such systems could be deployed efficiently and which types of next generation biomass technologies that accommodate BECCS in the most efficient manner.

Relevant research actions and questions are:

- How to best apply BECCS to pulp/ethanol/CHP/power/biogas/FT biomass conversion/novel technologies systems? Which capture technologies should be used?
- Transport and storage of the relatively smaller amounts of CO_2 in relation to FECCS? FECCS-BECCS co-benefits?
- How should specific countries' biomass systems be constructed to enable BECCS in a combined emissions mitigation, sustainability and economic optimization framework?
- How should specific countries' CCS systems be constructed to enable BECCS in a combined emissions mitigation, sustainability and economic optimization framework?

D. **Economic bottom-up models for regions and countries for short and mid-term BECCS deployment**. Most long term scenarios suggest massive BECCS deployment by 2050, but this means that there is a need for early phase implementation already during this decade.

a. Analyses of where BECCS could be implemented early, taking into account local biomass availability and CO_2 storage opportunities as well as CO_2 emission incentives and price structures.

b. Analyses of how incentive mechanisms need to be modified to include and incentivise BECCS, in order to achieve balanced portfolio deployment of BECCS (not too much, not too little). This is important in relation to other options such as solar and wind technologies, which in a number of countries have an entire set of incentives connected to them to facilitate early and long term deployment.

Relevant research actions and questions are:

- What is the right price/remuneration to BECCS developers/states?
- What is the right mix of incentives to achieve the rate of deployment that climate mitigation modelling calls for?

- How large is the current and 2020 potentials for BECCS in various cost, regulation and benefit frameworks?
- What are the early opportunities for BECCS deployment?
- How are these opportunities stimulated and incentivised most efficiently?
- What are the preferred steps of deployment?
- Which regions should take the lead?
- Which technology options should be implemented first?

E. **A comprehensive combination of the above studies** to assess the combined impact of costs, LCA impacts, biomass and CCS system integration and short and medium term regional deployment and expansion. This will yield a deeper and more comprehensive understanding of the global potentials and limits to BECCS in the climate mitigation portfolio.

Relevant research actions and questions are:

- How does BECCS fit into the overall mitigation portfolio?
- In what ways does the introduction of BECCS affect international climate mitigation negotiations (such as the UNFCCC process)?
- How do land use sinks, BECCS, direct CO_2 capture from air and other potential CO_2 sinks interact?
- How will they interact in a future restricted by various economic, political, technological and sustainability concerns?
- How are such interactions optimized with mitigation and adaptation strategies?
- Will the possibility of negative emissions give rise to a moral hazard when BECCS (and other sink creation methods) becomes available, diminishing the willingness to act now as present emissions could be counterweighted in the future with negative emissions? How to handle such a hazard?

5. Discussion and recommendations

5.1 Level of activity in research and development

Currently, there is no dedicated research funding for BECCS. The research that has been carried out to date has been funded through other efforts. In discussions with researchers within the area, it has appeared that one has received funding for BECCS specific activities, but rather for related fields of knowledge such as CCS, biomass energy, land use, climate scenario modelling etc. This, in combination with the cross-disciplinary feature of the subject has led to a sprawling and non-coordinated research pathway, limiting the ability for researchers to build on each others' work.

Since BECCS is cross-disciplinary, the study and development of the field has suffered from limited promotion by research facilitators and industry actors. Neither the CCS nor the biomass communities have yet adopted BECCS as part of their core strategies, and this have been a very important factor explaining the low intensity of BECCS research, development and deployment. The lack of advocates has contributed to the situation with no dedicated research funding for BECCS, as there is for most other technologies and disciplines relating to solving the climate challenge.

Although there have been discussions about the BECCS technology at several international conferences during the last years, usually as part of biomass and/or CCS-focused tracks. Still, these activities are very limited in scale and scope compared to the activities in the biomass or CCS areas where monthly conferences (often with both academic and industry representatives) are held all over the world, in some cases attracting thousands of participants.

The comparatively small body of published papers and the low degree of coordination among researchers (and among researchers, industry representatives and policymakers) does not stand in relation to the relative importance of BECCS for climate change mitigation.

5.2 Knowledge of BECCS in the research community and among decision makers

In general, it could be said that the dissemination of knowledge of BECCS is poor at the moment. Many peer-reviewed climate change mitigation scenarios do not account for or include BECCS, indicating that not even all members of the expert community have knowledge of BECCS. [41] This could be the result of the cross-disciplinary and complex nature of the technology, as mentioned earlier. Therefore, there is a

[41] See Clarke et al., 2009

need for increased awareness of the characteristics, the potential as well as the limitations of BECCS in the broader research community.

BECCS is rarely included into policy considerations. A substantial effort is needed to raise the awareness also among policy makers and politicians on BECCS, as this technology brings about a new set of considerations including negative emission accounting and incentivising, biomass-CCS system coordination and a need for complex long term system integration strategies to accommodate for BECCS.

In addition to the research and policy maker communities, very few in the general public know about BECCS and other negative emission technologies. There is a need to raise the awareness of BECCS, in order for voters, opinion leaders and businesses to make informed and efficient decisions.

5.3 Implications of findings for MISTRA strategies

This study highlights three areas where more work is needed:

- Co-ordination and dissemination of knowledge on BECCS
- Filling of research gaps as indicated in chapter 4
- Real projects to create learning-by-doing and input data for further research

Considering Mistra's mandate and mission, there could be a role for Mistra in all of these three areas, depending on ambition and resources at hand. Knowledge dissemination would be less costly than a full blown program, which on the other hand would provide critical input to the field. A BECCS demonstration program is potentially the most expensive option, but would need further consideration before the exact costs and program layout could be established, as this could be carried out in tandem with the considerable CCS and biomass programs of other international R&D funders.

5.4 Recommendations

Based on the findings of this study, the recommendation is to initiate an international researcher and decision maker knowledge dissemination program and as part of that effort prepare and launch a call for a BECCS R&D program that would focus on the research questions identified in chapter 4.

References

This section is divided into two parts, one with the database of peer reviewed BECCS articles, and one with other references used by this report.

The database used for the literature review presented in this report was collated through a bibliometric approach, i.e. the identification of articles based on occurrences of specific words in the article text. Specifically, searches on the terms BECCS, BECS, bio-CCS (etc. etc.) were conducted in a number of major scientific publications databases including Highwire Press, DOAJ/Directory of Open Access Journals, New York Times Archive, ScienceDirect, Science Magazine, Scopus, SpringerLink, Web of Science (ISI) with Conf Proc and Wiley InterScience. This was aimed at both peer-reviewed journals and studies published in other types of outlets. These systematic searches were complemented by cross-reference checks of articles cited in other work as addressing the topic of BECCS, as well as by the authors' own knowledge of ongoing studies in the area.

In a subsequent step, a careful reading of all articles was undertaken in order to exclude those with no or very limited discussion of the subject matter. Eventually, 67 peer-reviewed articles on BECCS published between the years of 1996 and 2010 were identified, along with 36 papers appearing in other outlets (including conference proceedings and working papers), as well as a number of non-BECCS articles. Given the varying quality of the non-peer reviewed type of work, a decision was made to base the current literature review only on the content of the peer-reviewed articles. As evident from above, however, some exceptions to this principle were judged permissible, notably when discussing the first mentions of BECCS and ongoing work.

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