A Strategy for Early Deployment of BECCS in Basic Industry - A Swedish Case Study

Deployment of BECCS in basic industry - a Swedish case study

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Abstract

This work discusses the potential for deployment of BECCS in Swedish basic industry as part of the portfolio of technologies and policy measures required to meet near zero emission targets. Since existing policy measures are too weak to incentivize investments in CCS/BECCS at a scale that would be in parity with the emission reductions required, and, since measures that could stimulate reductions in biogenic carbon dioxide emissions are still absent, we also explore key steps required to lay the groundwork for CCS/BECCS deployment. This includes; e.g., RD&D funding, governmental risk sharing and state funding to 1st of the kind projects, support for niche markets (e.g. through public/private procurement), market making for zero- (and/or negative-) CO2 products, and adaptation of infrastructure policies.

1 Introduction

Under the Paris Agreement the signing parties has set out to 'holding the increase in the global average temperature to well below 2 °C', and 'to pursue efforts to limit the temperature increase to 1.5 °C' above pre-industrial levels. Modelling work dedicated to exploring global mitigation scenarios that could meet these goals almost unequivocally stresses the importance of rapidly transitioning to zero- and low-carbon energy options, improving energy efficiency and radically reducing emissions related to land use, land use change and forestry [1]. In many cases these global mitigation scenarios, compatible with 'a well below 2 °C goal', also rely on net carbon dioxide removal accomplished to a large extent through large-scale application of BECCS, and afforestation [1-3]. These global deep decarbonization scenarios not seldom envisage a future where several gigatons of carbon dioxide of biogenic origin is captured and stored. The feasibility and appeal of such a large-scale deployment and sustainable implementation of BECCS has however been questioned. Deployment of BECCS on the gigatons scale would increase competition over limited biomass resources and possibly also result in competition with food production and biodiversity [4]. Despite this, much point in favour of that implementation of BECCS, perhaps at a more modest scale than first foreseen, will be an important part of the portfolio of technologies and policy measures required if the international community intends to commit to a well below 2 °C climate target.

Whereas the largest BECCS potential is considered to be in the electricity sector [5] targeting processing industries that already rely on biomass as raw material and fuel such as pulp and paper and ethanol plants, biogas refineries and biomass gasification plants may provide opportunities for early deployment of BECCS [6, 7].

Sweden has, in line with the Paris agreement, committed to reducing GHG emissions to net-zero by 2045 and to pursue negative emissions thereafter. This study seeks to explore how implementation of bioenergy with carbon capture and storage (BECCS) in Swedish basic industry could contribute towards achieving net-zero or negative territorial emissions towards the middle of the century.

Sweden, with a large bioeconomy, and Swedish industry, where biogenic emissions from large industry point sources accounts for a significant share of the territorial CO_2 emissions, may be well positioned for deployment of BECCS [6-10]. If accounting for both fossil and biogenic carbon dioxide emissions three energy- and emission-intensive industrial activities, pulp and paper, iron and steel production, and cement manufacturing, account for approximately half of the total domestic emissions. Thus, these industries are central in any strategy to meet national GHG emission reduction targets. Gardarsdottir et al. [11] show how implementing CCs/BECCS at both fossil and biogenic industrial sources in the Swedish process industry (>0.5 MtCO2/year) would be less costly and make it easier to meet national emission targets than if targeting only fossil sources. However, the extent to which industrial BECCS can be expected to contribute towards lowering emission depends both on the respective industries own priorities with respect to the future direction of technological development and the willingness and ability of the society as a whole to create favorable economic and organizational conditions for development, upscaling and commercial deployment.

The article is organized as follows. Section 2 provides an overview of technological options, in various stages of development, that could contribute to decarbonizing industry. Section 3 explores how implementation of BECCS in Swedish pulp and paper, iron and steel, and cement industries fits in to the respective industries strategic plans. Section 4 explore key steps required to lay the financial and organisational groundwork for CCS/BECCS deployment. Section 5 conclude by summarizing findings and identifying promising areas for future research.

2 Technologies for decarbonizing the energy and carbon intensive industry

The main message from the branch of academic literature devoted towards the challenges associated with decarbonizing industry is relatively coherent (see e.g., [12, 13]). The general message is that while there still is an untapped potential for further emission reductions through presently available measures and technologies, reducing CO_2 emissions beyond a certain point will involve significant investments and substantial changes to conventional manufacturing processes. A range of technological and process abatement options, in different development stages, that could, potentially, contribute to reducing emissions from manufacturing of CO_2 emission-intensive commodities (e.g. pulp and paper, steel, cement, chemicals and plastics) have been proposed. Table 1 provides an overview of technological and process abatement options, in different stages of development, in the pulp and paper, steel, cement industries and Figure 1 provide rough estimates of the abatement potentials. We have chosen to group and present the abatement options in four different categories – with different characteristics with respect to for example choices of energy carriers, process designs and the availability of CCS:

- Direct electrification
- Electricity/hydrogen
- Biomass
- CCS

Table 1. Overview of technological and process abatement options, in different stages of development, in key energy- and emissions intensive basic industries.

	CCS/BECCS	**Biomass/bioenergy**	**Electrification**	**Renewable hydrogen**
Pulp and paper *See e.g.: [14, 15]*	• Existing Kraft pulp w/ CCS (Recovery boiler, the lime kiln and the multi-fuel boiler) • Black liquor gasification w/ CCS • Bio-refinery w/CCS	• Biorefinery integration. Maximising the utlization of forest product residues and/or other lignocellulosic raw materials by co-producing, e.g., biofuels and/or specialty chemicals.	• Hybrid boilers with dual fuel systems (electricity + biomass) • Expansion of internal backpressure capacity	Limited applicability
Iron and steel *See e.g.;* [16, 17]	• Conventional integrated production (BF/BOF) w/ CCS • Fossil direct reduction w/ CCS	In the conventional (BF/BOF) route: • Incorporation in the charging material • By gasification to generate gas for reduction or heating • By injection into the blast furnace In the secondary (EAF) route: • Replacing graphite electrodes with biomass	• Increased secondary scrap-based production in electric arc furnaces (EAF) • Electrowinning	• Hydrogen direct reduction
Cement industry *See e.g:* [18, 19]	Targeting process and/or fuel related CO_2 emissions, through. • Post-combustion capture • Partial or full oxy-combustion with CO_2 capture • Partial or full electrification w/ CCS	• Replacing conventional fuels (typically coal and pet-coke) with biomass-based fuels	• Partial or full electrification. Substituting fossil fuels with renewable electricity to supply process heat	Limited applicability

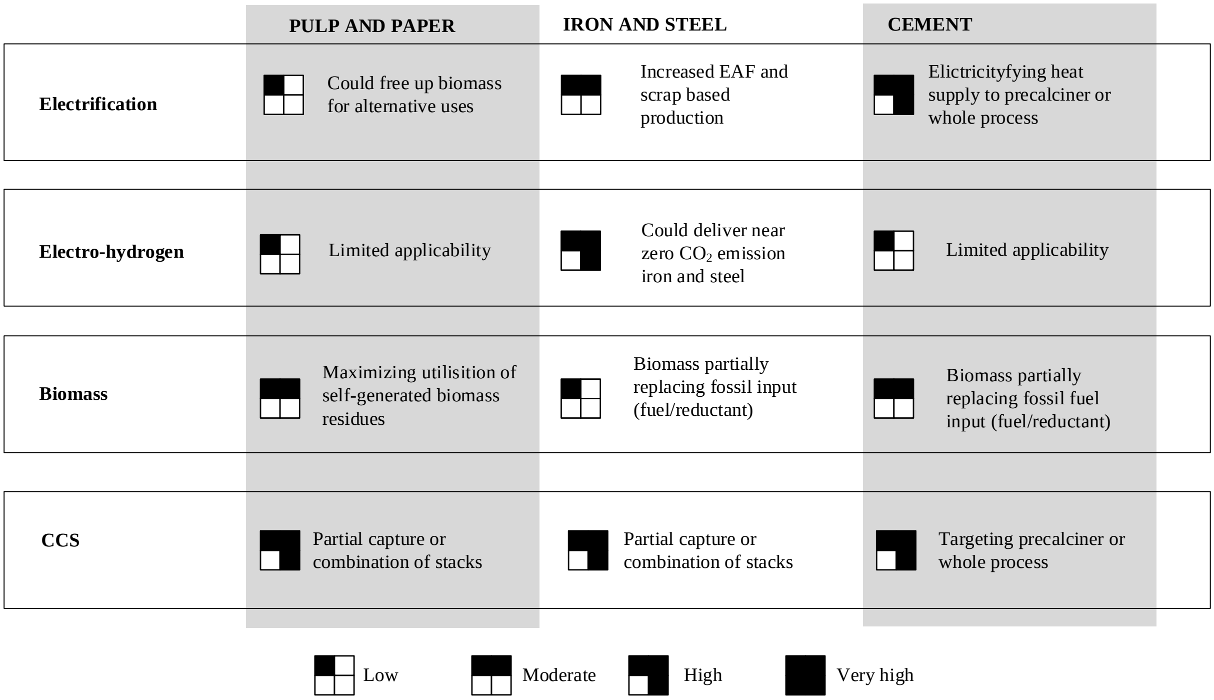

Figure 1. Abatement opportunities and gross estimates of the abatement potentials the in pulp and paper-, steel- and cement-industries.

Whereas successful decarbonisation in many cases will require the deployment of a combination of measures from these four categories of technological abatement options there are also crucial differences between the categories in terms of the support infrastructures required (RES electricity supply, power transmission capacity, hydrogen and biomass production and logistics, CO_2 transport and storage infrastructure) and with respect to the interplay between industry and the wider energy system. How industries in the respective industry sector prioritises between these different categories of abatement options will obviously have implications for the future role of BECCS – a move towards increased electrification can for example be expected to lead to less opportunities for BECCS. In light of the long investment cycles involved in capital-intensive industries, such pulp and paper plants, steel works and cement plants this illustrate how strategic decisions with respect to technological development taken in the near future will affect the extent to which deployment of BECSS in the basic industries can contribute towards achieving net-zero or negative CO2 emissions towards the middle of this century.

A fifth category of abatement measures, which the industry does not control, but that could have implication for the need for BECCS includes measures to reduce or dampen demand for primary material production through material efficiency and material switching. Encouraging and incentivising, e.g., re-use, recycling efficient design are important in any strategy to achieve significant reductions of CO2 emissions associated with primary production of basic materials and goods [20, 21]. However, there are also important counteracting trends from projected increase in demands for materials due to new investment and re-investment needs in buildings and infrastructure [22](Monteiro et al., 2017). Also, the low-carbon transition in the transport and energy sectors, is expected to put upwards pressure on the demand for basic materials and goods. In addition, from a national perspective, since many commodities are traded globally, effort to improve material efficiency and reduce material demand in one country does not necessarily lead to reduced production levels in the same country.

3 Bioenergy and BECCS in Swedish industry

3.1 Pulp and paper

The pulp and paper industry is the largest industrial energy user in Sweden. Fossil fuels have largely been phased out and the majority of the energy need is met by internally derived biomass. Total annual emissions of carbon dioxide from the approximately 50 pulp and paper mills (including plants for the production of mechanical pulp, chemical pulp, paper and paperboard) currently in operation in 2015 were 21 MtCO2/year - 97% of which was of biogenic origin and 3% from the combustion of fossil fuels.

With respect to final products, energy use and CO2 emissions the pulp and paper industry can be divided into three subsectors: chemical/kraft pulp (and paper) mills, mechanical pulp (and paper) mills, and pure paper mills without any virgin pulp production [14].

In the short term the most promising option for implementation of BECCS in the pulp and paper industry would be to capture CO2 from the flue gases from the recovery boiler or from a combination of stacks (recovery boiler, lime kiln and multi-fuel boiler) at existing Kraft pulp mills. If and when black liquor gasification is introduced or if pulp and paper industries begins to diversify their process and product portfolios towards e.g. biofuels and/or specialty chemicals production (i.e. biorefining) new opportunities for CO2 capture and BECCS may emerge.

However, the pulp and paper industry, which today is the major source of biogenic emissions in Sweden have, in the absence of a mechanism to reward negative CO2 emission, little or no incentives to opt for BECCS.

3.2 Integrated iron and steel

SSAB's integrated iron and steel production plants in Luleå and Oxelösund are the largest point sources of fossil CO2 emissions in Sweden. The Oxelösund plant includes the entire production line, extending from raw materials to rolled plate. At the Luleå plant, which does not have a rolling mill, steel slabs are the final product. The final stages of the steel processing are carried out in Borlänge where SSAB has hot and cold roll mills in addition to coating and finishing lines. All of the three blast furnaces (one in Luleå and two in Oxelösund) use iron ore pellets, which are mined and processed in Sweden, as the main raw material input. Fossil fuels currently dominate all production steps: iron ore pelletising (coal and fuel oil), integrated iron and steel production (coke, which is derived from coal) and final processing (fuel oil and liquefied petroleum gas). The most promising option for implementation of BECCS in steel industry would likely be to introduce CO_2 capture at the integrated steel plants in Luleå and Oxelösund while at the same time replacing coal/coke with biomass/bio-coke. Whereas SSAB previously have investigated both CO2 capture and the possibility to introduce biomass/bio-coke the company is currently considering a shift to a completely different production process. SSAB has together with mining company LKAB and energy company Vattenfall recently launched a joint venture aimed at developing processes for CO_2-emission free iron- and steel-making. The centrepiece of the project is the Hydrogen Breakthrough Ironmaking Technology (HYBRIT). The idea is to replace the blast furnaces with an alternative process, using hydrogen produced from “carbon neutral” electricity, to reduced iron ore. While the HYBRIT concept would also require significant amounts of biofuels (to replace fossil fuel in the iron ore pellitising and in the final processing) [23] the opportunities for BECCS would most likely be smaller.

3.3 Cement manufacturing

Cementa, which is a subsidiary to the HeidelbergCement group, owns the three remaining cement plants in Sweden. The plants, which are located in Slite, Degerhamn and Skövde, together have a capacity of approximately 3 Mt cement/yr. The largest of the three, the Slite plant, accounts for more than 70% of Swedish cement production. With a market share of 90% Cementa dominates the Swedish market and one-third of the production is exported. With high absolute levels of CO2 emissions and relatively high concentrations of CO2 in the flue gas streams (~20%), the cement industry is an early candidate for the implementation of CCS. Recognising this, the development of CCS is together with efforts to icrease the use of biomass fuel, an important part of an overall mitigation portfolio for the Nordic subsidiaries of HeidelbergCement (Norcem (Norway) and Cementa (Sweden)). Cementa recently also initiated a pre-feasibility study aimed at exploring possibilities to electrify the cement making process – substituting fossil fuels with renewable electricity to supply process heat. However, since the majority of the emissions from the cement making process originates from the calcination of limestone, electrification will only solve parts of the problem. Taken together, the Swedish cement industry is currently the actor with the largest stake in a successful deployment of BECCS and CCS.

4 Laying the financial and organisational groundwork for BECCS

For BECCS, or any other deep decarbonisation option, to contribute meaningfully to industry emission reduction within the next few decades efforts to create favourable economic and organisational conditions have to be ramped up drastically over the next decade. This involves for example adaptation of legislation, innovative schemes to share the risk and costs associated with developing and implementing new technology. A functioning BECCS scheme rely on three fundamental components; I. Incentives to reduce biogenic CO2 emissions and mechanisms to reward BECCS and negative emissions, II. adequate and sustainable supply of biomass/biofuel, and III. technical implementation of the CCS chain, i.e. Capture, Transport and Storage. Apart perhaps for mechanisms to incentivise reductions in biogenic CO2 emission all of these individual components have been proven, in various applications and at varying scales. However significant development work still remains in the different parts of the chain before BECCS could be deployed at scale. In the following subsections we review and propose incentive mechanisms that could facilitate, A. Development and demonstration, B. Upscaling, and C. Commercial deployment, in the different parts of the BECCS chain.

4.1 Incentives to reduce biogenic CO2 emissions reward BECCS and negative emissions

An obvious and major hurdle for BECCS is that there are currently no incentives to reduce emissions of CO_2 molecules of biogenic origin and even less incentives to capture, transport and store such molecules. Whereas the 2006 IPCC Guidelines for National Greenhouse Gas

Inventories allow CO2 emissions for negative emissions from BECCS to be recorded and recognised in national greenhouse gas inventories [24] the regional cap-and-trade schemes currently in force, including the EU ETS, does not recognise and reward BECCS and negative emissions in general [25, 26]. The most obvious way to incentivize BECCS would seemingly be to make negative emissions from BECCS eligible for credits under the EU ETS. Other potential complementary incentive mechanisms, which could be implemented on a national or regional (e.g. Nordic) level includes: Feed-in-tarrifs, reverse auctions and certificates. [5, 6, 24, 27].

4.2 Adequate and sustainable supply of biomass/biofuel

Any valid BECCS strategy must take into account that a move away from fossil fuels will most likely lead to increased competition for biomass globally as well as nationally. One way to avoid adverse side effect would be to limit biomass use to feedstock from sustainably managed forests [28] and/or to feedstock that either would be wasted or is grown in excess of what would have grown absent the demand for bioenergy [29]. While biomass expenditures would most likely increase, this should be fairly easy to comply with for the pulp and paper industry, which generates and utilises biomass wastes and residues as part of their operations, and for the cement industry, which typically uses wastes as a supplementary fuel. The iron and steel industry, where quality specifications can be expected to be stricter and where new biofuel supply chains would need to be mobilised, might find it more difficult to comply with stricter biomass standards.

4.3 Capture

Application of CO_2 capture has till now mostly been limited to high-purity sources like natural gas processing and fertilizer production. Development of large scale projects has been slow and there are currently only a few commercial-scale carbon capture power plants in operation (Boundary Dam (Canada) and Petra Nova (US), both capturing in the range of 1 $MtCO_2$/year). While important lessons can be learned from these experiences, implementation of CO2 capture in basic industry will be process and site specific. Factors such as the specific process employed the number of stacks, the composition of different flue gas flows, the availability of excess heat, the age structure of the capital stock, technology and fuel mix, the geographical location and spatial distribution of the plant will have implications for how, when and at what cost BECCS can be applied. A rollout of BECCS at scale towards the middle of this century requires extensive research and development effort in the coming decade to pin down the most suitable capture technology in different industrial applications, to decrease technological uncertainty and to minimize CO2 capture cost. While significant technical, infrastructural barriers also remain to be resolved, currently, the inability to incentivize and raise capital to finance such development remains the most important hurdle to the uptake of alternative low-CO2 technologies for applications in the basic industry. Potential funding arrangements includes:

- Inclusion of consumption of carbon intensive commodities in the EU ETS [30, 31]. A consumption charge would be levied on products containing carbon intensive materials (e.g. steel and cement) and the resulting revenues can be used to directly fund innovation towards low- (or negative-) CO_2 emissions process technology.

- Public-private risk sharing arrangements, e.g., joint venture or loan guarantees.
- The creation of a private or public private transformation fund where actors along the supply chain for carbon-intensive materials like cement and steel take part in the risk sharing and direct funding [32].
- Subsidies in the form of direct payments or tax credits

Other preparatory steps include

- Reviewing of existing planning and permitting systems. One option to avoid stalling BECCS deployment at a later stage could, for example, be to require assessment of potential for CO_2 capture/capture readiness before permitting new thermal units (>X MW) (as part of environmental impact assessment) and high purity CO_2 sources (e.g. large-scale fermentation).

4.4 Transportation

Irrespective of the mode of transport (i.e. ship or pipeline or a combination of these) a functional national or regional CO2 transport infrastructure would need to be capable of safely handling tens of millions of tonnes of captured CO2 annually. Planning and coordination of such an infrastructure will involve overcoming significant barriers associated with risk and uncertainty. Planning, investment and development will eventually need to be commenced independently of individual capture projects [33] Early groundwork would include:

- Feasibility and routing studies to dimension the infrastructure.
- Inventory of potential areas of national interests for CO_2 infrastructure, e.g. harbours, hubs, pipelines, intermediate storage (cf. existing dedicated areas of national interest for energy production, wind power, energy distribution).
- Developing a strategy for ramping-up transportation capacity over time.
- Long term signals and incentives for potential transport operators (that would own and oversee the everyday operation of the transportation infrastructure).

4.5 Storage

To be complete a BECCS strategy will need to sort out where and under what regime CO_2 will be stored. Early priorities include:

- Inventories of potential storage sites (domestic and international) that could match the storage needs. Suitable storage sites need to fulfil several specific requirements, e.g. overall storage potential, injection capacity (governing the rate at which CO_2 can be injected in the reservoir) and the long-term integrity of the geological formation (guaranteeing that CO_2 will be completely and permanently contained).
- Preparations of institutional arrangements that would govern roles and responsibilities with regards to, e.g., enforcement of monitoring and verification of the storage site and long-term liability for stored CO_2.
- Long term signals and incentives for potential storage operators (that would own and oversee the everyday operation of the injection facilities).

- Dialogues with neighbouring countries to explore possible cooperation arrangements for developing and scaling up transport and storage solutions

Initial inventories suggest that the best option from a Swedish perspective would be to transport CO_2 for final storage in reservoirs in the Skagerrak region or in the Norwegian North Sea where more well-developed sites exists [34]. Another possibility would be to develop storage sites in the Baltic Sea. The Geological Survey of Sweden [35] has identified two areas in the Baltic Sea with favourable conditions for geological storage of CO_2. Early assessments suggest that the storage potential in these areas may suffice projected future needs. However, additional, rigorous, investigations are required to verify storage and injection capacity before storage could be commenced.

4.6 Collective action

If to pursue BECCS at scale, development of the different components (Incentives to reduce biogenic CO2 emissions and mechanisms to reward negative emissions, Adequate and sustainable supply of biomass/biofuel, Technical implementation of the CCS chain, i.e. Capture, Transport and Storage. Capture, Transportation and Storage) and dimensions (e.g. Technology, Infrastructure, Legislation and Incentive mechanisms) would need to be pursued in parallel. In this regard, the challenge associated with BECCS implementation exhibits some of the features that often characterize collective action dilemmas [36]. While sharing the same overarching goal, negative emissions from BECCS, one of the challenges will be for the different actors involved in the BECCS chain to find strategies to move forward at the same pace [37]. The basic materials producer needs some form of assurance that an investment in a mitigation measure will repay itself, through compensation for negative emissions from BECCS and/or through selling net-negative products at a higher price. Before investing in capture the basic material producer would also need some type of guarantee that functional systems for transport and storage will be in place, at a reasonable and predictable price. Transport operators need to have confidence in that investments in CO_2 capture will be materialised and of a functional storage solution. Storage operators need a guarantee of income before they can invest in exploration of storage sites and

As a way to coordinate collective action the Norwegian NGO Bellona [37] has proposed the establishment of a regional coordination body, a 'Market maker' that would:

1. Manage the development of primary infrastructure on behalf of the state (e.g. pipelines, shipping terminals and back-up storage sites)
2. Committing to take all contracted captured CO_2 and ensure corresponding storage capacity is available.

Similarly, Banks et al. [33] argue for the need to form regional coalitions initialised by public sector institutions with common interest in constructing, operating and utilizing offshore storage sites and transport infrastructure servicing industrial capture clusters and aggregating networks.

5 Concluding discussions

The assessment presented in this paper is, as the title suggests, contextualised. Sweden with rich forest resources and a relatively large bioeconomy are in some senses a special case. Still some of the findings and propositions are applicable also elsewhere. A realistic assessment of the extent to which deployment of BECCS in basic industry can be expected to contribute to climate mitigation need to consider the current direction of technological development in the respective industry and the development trends in the surrounding energy system. Strategic decisions with respect to technological development taken in the near future will affect the extent to which deployment of BECSS (or any other decarbonisation option) in basic can contribute towards achieving net-zero or negative CO2 emissions towards the middle of this century. Based on these propositions we argue that, in a Swedish context, the cement industry is probably currently the actor with the largest stake in a successful early deployment of BECCS and CCS even though the pulp and paper industry, with large internal biomass flows, holds the largest overall potential for BECCS deployment.

Climate policies that target the industrial sectors, in Sweden and the rest of the EU, continue to rely almost exclusively on the price signal imposed through the EU Emission Trading System (EU-ETS). However, the price range expected for emission allowances under the EU ETS for the period up to Year 2030 (Carbon Tracker, 2018) will not suffice to drive the development of BECCS or other high-abatement, high-cost measures discussed in the previous sections. Thus, irrespective of the technology and process abatement option of choice the ability and willingness today to devise and implement mechanisms (e.g. cost and risk-sharing arrangements) that could unlock investments in development and upscaling of transformative technologies will most likely be instrumental if basic industry is to contribute towards achieving net-zero or negative CO2 emissions towards the middle of this century.

While significant technical, infrastructural barriers also remain to be resolved, currently, the inability to incentivize and raise capital to finance development and commercialisation remains the most important hurdle to the uptake of alternative low-CO2 technologies for applications in the basic materials industry.

Acknowledgements

Financial support from VINNOVA (2016-03387), the Swedish innovation agency, is gratefully acknowledged.

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