CCS in industry:
the case for an undervalued mitigation option

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Executive Summary

Deep greenhouse gas (GHG) emission reductions in the industry sector to achieve climate stabilisation targets will be difficult to attain without recourse to CO_2 capture and storage (CCS) systems. Using a bottom-up energy system model with cost optimisation running to 2100, as well as a short-term engineering cost review, this paper investigates the case for CCS in industrial sectors, including in developing countries. It concludes that there are various technical pathways for CCS to play a critical role in mitigation strategies and that CCS in industry has more advantages than CCS in the electricity sector. CO_2 capture costs are, in many cases, lower in industry than in the power sector. Excluding CCS in the power sector from the portfolio of mitigation options increases total cumulative climate policy costs of a 2°C temperature stabilisation scenario by USD 34 trillion until 2100 (some 10 % increase compared to the case in which CCS is availability for all sectors). Even higher costs occur if CCS technologies are excluded from the mitigation portfolio of the industry sector. In this case, cumulative climate policy costs increase by USD 175 trillion until 2100, corresponding to additional 50 % of the policy costs of the scenario with full availability of CCS and five times more than the additional policy costs of the case that CCS is excluded from the electricity sector mitigation portfolio. CCS also seems to be more acceptable to social and environmental advocates if applied in industry, as opposed to the power sector where it may have an impact on renewable energy deployment. In order for CCS in industry to play a global role in climate change mitigation, it will need to be as much a priority in developed as in developing countries. Thus, policy and research activity should include international interventions in specific industrial sectors and in the development of biomass and CCS systems that could lead to an improved enabling environment for CCS in industry.

Table of Content

Abbreviations

bcm	billion cubic meters
CCS	CO_2 capture and storage
CDM	Clean Development Mechanism
CO_2	Carbon dioxide
CO_2-EOR	Enhanced Oil Recovery using CO_2
CO_2-EGR	Enhanced Gas Recovery using CO_2
CTL	Coal To Liquids
ECBM	Enhanced Coal Bed Methane recovery
GtL	Gas to Liquids
IEA	International Energy Agency
IEA GHG	IEA Greenhouse Gas R&D Programme
IPCC	Intergovernmental Panel on Climate Change
UAE	United Arab Emirates
UNFCCC	United Nations Framework Convention on Climate Change

1 Introduction

It is difficult to imagine climate stabilisation without a role for CO_2 capture and storage (CCS). The technology has developed over the past years primarily with a view on application in fossil-fuel power generation. What has often been overlooked, however, is that CCS is one of the most important CO_2 mitigation options for many industrial sectors, much of global industry depends heavily on fossil fuels as a feedstock and energy source. Until, for instance, steel and cement are replaced by alternative materials, plastics are bio-based, and oil is replaced by other liquids, global emission reductions of 80% or more are hard to imagine without CCS in several industrial sectors.

Still, the bulk of political attention and investments in CCS are targeted at CCS in coal-fired power plants. As an example, the 2012 Global Energy Assessment (GEA, 2012) addresses almost exclusively CCS in coal-fired power. The IEA/UNIDO Roadmap on CCS in industrial applications (IEA/UNIDO, 2011) is a notable exception, as well as several sector-specific contributions (Jönsson and Berntsson, 2012; Straelen, 2009), but they have not translated into policy attention. This paper aims to contribute to achieving long-term climate goals by investigating the case for a concerted policy effort for CCS in industry.

There are several other reasons to take a closer look at CCS in industry. First, costs for CCS in industry are often lower than in coal-fired power, making its deployment more viable (IEA, 2009; IEA/UNIDO, 2011). Second, as CCS in industry is unlikely to displace investments in renewable power, it may be more acceptable to environmental organisations (CAN, 2010) and potentially to the general public. Third, given the characteristics of many industrial sectors, with high-technology, multinational companies with risk-seeking characteristics, the deployment of CCS in industry is more likely than in the power sector, also enabling green industrialisation in developing countries (IEA/UNIDO, 2011).

This paper is structured as follows. First, we briefly discuss the context and state of CCS and, using a perfect-foresight, bottom-up global energy system model with cost optimisation up to 2100, the consequences of having CCS available for a climate change stabilisation scenario. Subsequently, we investigate the case for CCS in industry in three steps: we discuss technical and general cost aspects of CCS in industry, we project how CCS availability in different sectors affects overall climate stabilisation costs and viability in what is essentially a sensitivity analysis for CCS in a global energy model, and we discuss socio-political aspects of CCS. Finally, we conclude with a potential way forward in terms of policy and research actions, including for a green industrialisation agenda in developing countries.

2 Consequences of excluding CCS from the mitigation portfolio

CO_2 capture and storage is a mitigation option that involves the separation and in most cases the purification of CO_2 from a stationary point source, its transport and its storage in a deep geological reservoir that has been selected on its properties to retain the CO_2 permanently (IPCC, 2005). Parts of the techniques used for CCS are well-known through commercial application in the oil and gas industry (IPCC, 2005), but in order to lower costs in other sectors and build a safety record, continued R&D and demonstration are needed (Coninck et al., 2009; IEA, 2008). Full-scale demonstrations of CCS are implemented in several countries (GCCSI, 2012), but many have also been cancelled for technical, economic and social reasons (Stigson et al., 2012).

The TIAM-ECN model (Kober et al., 2012; Rösler et al, 2012; Keppo and van der Zwaan, 2012; Loulou, 2008; Loulou and Labriet, 2008) was used for our research in order to investigate the role of CCS for reaching the UNFCCC-agreed long-term climate target of global mean temperature increase by 2˚C (UNFCCC, 2010). Significant reductions of GHG emissions are necessary in this century, which requires a worldwide decarbonisation of almost the entire energy sector. In order to unlock all available GHG reduction potentials negative net GHG emissions might occur for selected world regions and energy sectors by the end of the century (Kober et al. 2013). Figure 1 shows that having CCS available (the “allCCS”-scenario) requires less strong GHG emission reductions of 2.3 $GtCO_2$ by mid-century compared to a scenario without CCS (“noCCS”). It also shows that the availability of CCS has a significant impact on the carbon price, which is twice as high in the second half of the century in the noCCS case compared to allCCS.

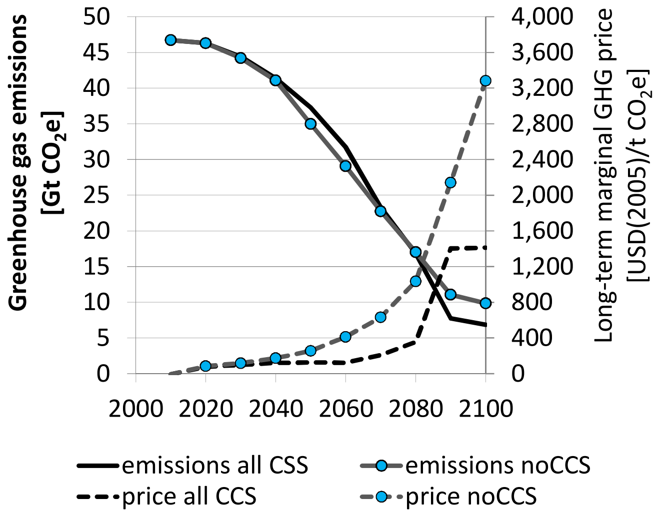

Figure 2.1 **Two global mitigation pathways: with (allCCS) and without (noCCS) CCS options included in the mitigation portfolio**

Figure 2.2 illustrates the difference in type of fuels and technologies that are used to meet the climate targets with or without CCS. The model uses relatively conservative estimates of maximum global biomass potential (about 150 EJ in 2100), reflecting biomass availability under the consideration of sustainability criteria and the prioritisation of food production issues (GEA, 2012; Hoogwijk et al., 2009; Thrän et al., 2010). It uses estimates of CO_2 storage potential at about 1000 $GtCO_2$, which is conservative (compare GEA (2012) and (IPCC, 2005)) taking into account that regional availability may be limited (the model only allows transport of CO_2 within its 15 regions) and that the economical and safe potential is considerably lower than the technical potential. The CO_2 storage potential includes saline aquifers, depleted and active hydrocarbon storage sites and coal seams. Combined transport and storage costs range between 9 and 24 USD(2005) per tonne of CO_2 stored.

With CCS, fossil fuels would account for 42% of the global primary energy consumption in 2100, while without CCS, renewable energy would contribute 85% of the global primary energy consumption in 2100. Especially solar energy would become important and contribute over 60% of electricity generation.

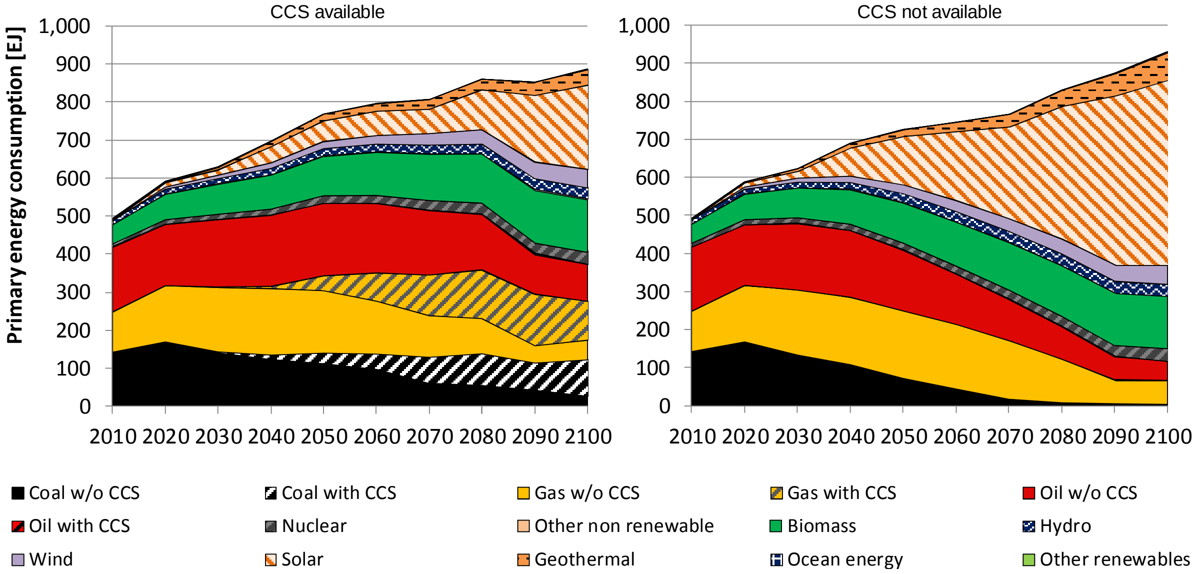

Figure 2.2 **Global primary energy consumption under a climate policy regime reaching the 2°C target with and without availability of CCS**

In the allCCS scenario, CCS technologies are applied both in industrialised and developing countries. Until 2100, about one third of the total of 930 $GtCO_2$ is captured and stored in China, India and the other South-East Asian countries. CCS in North and South America represents almost 25%, Africa and the Middle East 20% and Europe 10% of the world's total.

3 Current CCS technologies for industry

The application of CCS in Figure 2.2 comprises capture and storage of CO_2 from both the power sector and industrial applications, such as cement plants, iron and steel factories and upstream fuel facilities, such as hydrogen production facilities. CCS for such industrial processes has recently gained recognition by international organizations (GCCSI, 2012; IEA/UNIDO, 2011). Capture systems and separation technologies that were initially envisioned for application on coal and gas-fired power plants (IPCC, 2005) can also be applied to point sources in industry (IEA/UNIDO, 2011).

Other industrial CO_2 sources, referred to as 'high-purity', have by-product gas streams of highly concentrated CO_2 (i.e. >95%, although no strict definition exists). Such concentrated sources of CO_2 stem from *inter alia* steam methane reforming for hydrogen production, natural gas processing and ethylene oxide production (Zakkour and Cook, 2010). Currently, the share of such high-purity CO_2 sources is estimated at approximately 7% of total 2010 global industrial GHG emissions. (IEA/UNIDO, 2011). Capturing from high-purity sources can be achieved at much lower investment and operational costs compared to other sources, because the expensive and energy intensive CO_2 stripping technology is not needed. However an incentive is still necessary to cover compression, transport and storage costs.

As for cost controlling reasons many conventional processes in industrial sectors are already close to optimum operating efficiency, CCS will be necessary to reduce CO_2 emissions in order to reach the 2˚C target. Generally blast furnaces emit between 1.5 to 2.0 tCO_2/t of iron produced (IEA/UNIDO, 2011), with greenfield blast furnaces built according to best practice can achieve CO_2 emissions of 1.4 tCO_2/t (CAN, 2010). During primary steel production, between 65% and 75% of the CO_2 emissions arise directly from the use of charcoal or coke as a fuel and reductant for the blast furnace; the core process where iron ore is smelted to produce intermediary material for commercial iron and steel manufacture (Rootzen et al., 2009). A potential blast furnace modification, top gas recycling (TGR), involves the removal of CO_2 from the blast-furnace off gases, and re-injecting the primarily CO rich gas into the blast furnace. This can reduce CO_2 emissions of primary steel production by 10-20% compared to best practice (EC, 2009), and by 50% if CCS is also applied (CAN, 2010). Steel manufacturer ArcelorMittal has proposed to demonstrate TGR with CCS by 2016 as part of the ULCOS development project (Birat, 2010).

Similar reductions can be achieved through CCS in large-scale, modern cement production facilities. Point sources at a cement plant have relatively high concentrations of CO_2 (14-33%) compared to power plant emissions (Liu and Gallagher, 2010), which means that post-combustion capture could be applied to the plant without disrupting the core process at cost lower than coal-fired power plants (MottMacDonald, 2010), where CO_2 concentrations generally don’t exceed 15% (IPCC, 2005).

Refinery complexes (oil but also bio-based fuels) have many different CO_2 sources. The hydrogen production, which accounts for between 5-20% of total oil refinery plant emissions, can offer low-cost CCS opportunities (Straelen, 2009). In addition, through combustion with pure oxygen, the fluid catalytic cracking unit in a refinery can be retrofitted for CO_2 capture (CCP, 2010). Other sources of CO_2 in a refinery complex are less amenable for CO_2 capture (DNV, 2010).

The possibilities for CCS in industrial sectors are manifold and can lead to deep emission reductions, but require further technology demonstration and investment. The next section explores how this compares with the investments required in the power sector in the longer term.

4 Comparing the role of CCS industry and power sectors

In order to assess the importance of the availability of CCS technologies for the power sector and industry sector, we expand the scenarios in the previous section (allCCS and noCCS) with a scenario CCS(IND) in which CCS is exclusively available in the industry sector and the scenario CCS(PUB) in which CCS is only available for public electricity generation (Table 4.1).

Table 4.1 Scenario matrix: availability of CCS options in different energy sectors

Energy sector	CCS-all	CCS(IND)	CCS(PUB)	noCCS
Industrial production and upstream fuel conversion	CCS available	CCS available	CCS not available	CCS not available
Public electricity and heat production	CCS available	CCS not available	CCS available	CCS not available

Unpacking the numbers for CCS deployment in the left panel of Figure 2.2 reveals that 42% of the 930 $GtCO_2$ captured and stored underground in 2100 originates from the power sector, and 58% from industrial sectors (left panel in Figure 4.1). Of CCS in industry, 55% is captured in the fuel processing industry (refineries, synthetic fuel and hydrogen production) and 45% in industrial production processes (iron and steel, cement and chemical feedstock industry) (right panel in Figure 3). This is roughly consistent with earlier scenario work (e.g., IEA (2009)).

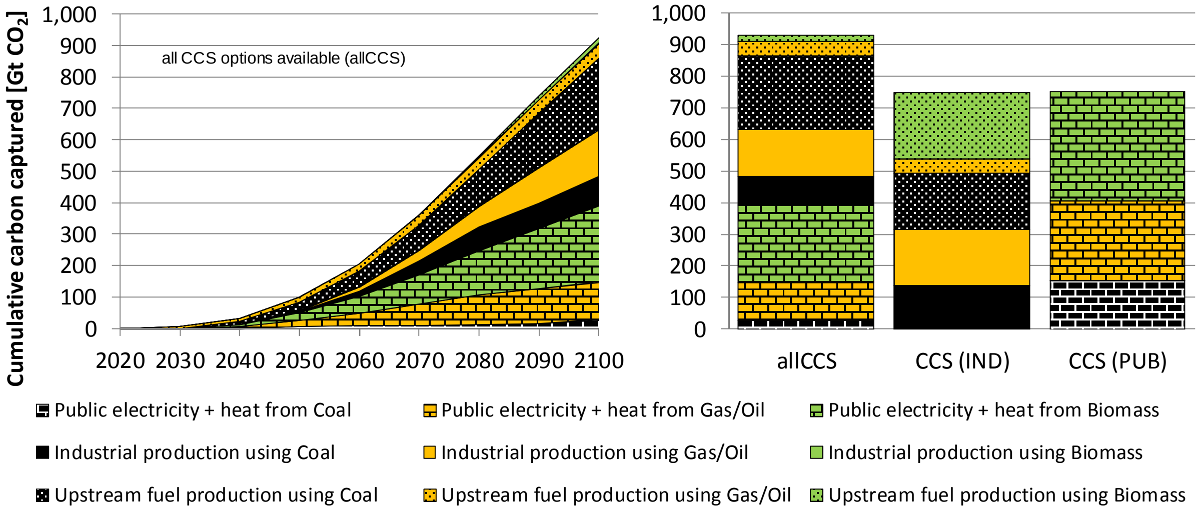

Figure 4.1: **Cumulative carbon captured worldwide from 2020 to 2100 in the case of full availability of CCS (left) and until 2100 at unavailability of certain CCS options (right)**

Unpacking the CCS deployment further, and comparing the scenarios CCS(IND) and CCS(PUB) in which CCS is only available in either industry or power and heat, to the scenario in which the availability of all CCS options is assumed (allCCS) a reduction of the total cumulative capture quantity by 2100 by about 15% to 750 – 780 $GtCO_2$ results.

Figure 4.2 shows the four scenarios for CCS availability in terms of fuel consumption and energy use in industry, illustrating vast shifts in fuel use. In the electricity sector, the availability of CCS for that sector but not in industry (CCS(PUB)) leads to, first, much higher electricity demand and, second, more use of gas and coal in electricity (see left panel in Figure 4.2). If CCS is available in industry, gas and coal remain dominant energy sources in this sector, while when CCS is not available, energy use in industry is dominated by electricity (middle panel of Figure 4.2). In the fuel transformation sectors, the availability of CCS in industry but not in the power sector (CCS(IND)) leads to a large share of biomass and CCS in the fuel consumption pattern (right panel of Figure 4).

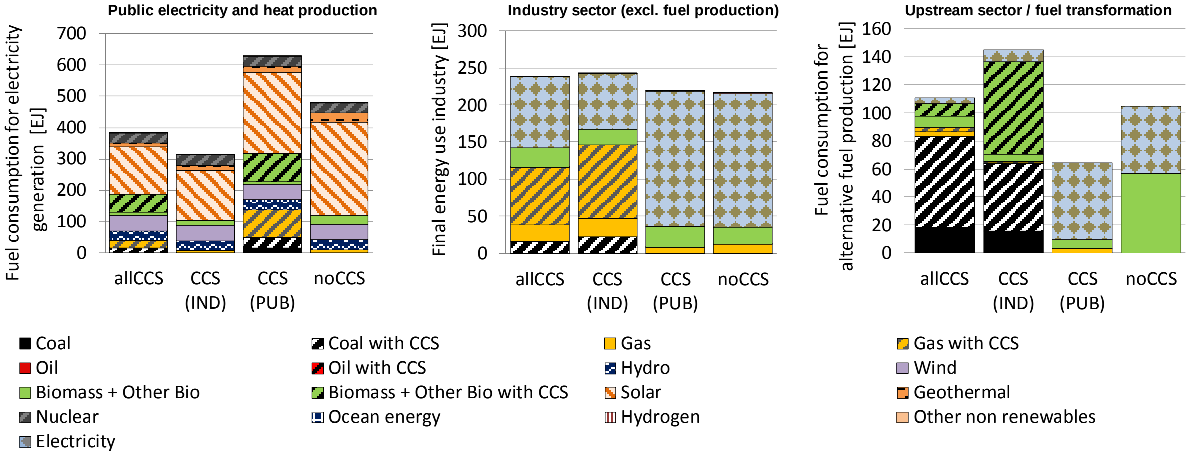

Figure 4.2: **Global fuel consumption in 2100 for the main CCS relevant sectors in four scenarios: with CCS availability in all sectors; with CCS availability only in industry (CCS(IND), including fuel transformation); with CCS availability only in the public electricity and heat sector (CCS(PUB)) and with no CCS availability.**

If CCS is exclusively applied in the industry sector, global cumulative carbon captured for hydrogen and synthetic fuel production increases until 2100 to 430 $GtCO_2$ and for industrial production processes to 320 $GtCO_2$. Global hydrogen and synthetic fuel production increases by 25% in 2100, whereas less coal and more biomass are used compared to the case that all CCS options are available. Consequently cumulative carbon captured for hydrogen and synthetic fuel production based on biomass increases until 2100 to 210 $GtCO_2$ and decreases for natural gas and coal to 220 $GtCO_2$. For industrial production processes both the cumulative capture quantities from natural gas (180 Gt CO_2 until 2100 in CCS(IND)) and coal (130 Gt CO_2 until 2100 in CCS(IND)) increase compared to scenario allCCS.

5 Comparing policy costs for different CCS availabilities

The global climate mitigation policy cost implications of different availabilities of CCS differ dramatically between the scenarios investigated. The numbers are summarised in Table 2, representing additional policy costs compared to the allCCS case, which accounts for cumulative climate policy cost of USD(2005) 42 trillion until 2050 and USD(2005) 362 trillion until 2100. If CCS is not available (noCCS), total policy costs to reach the climate targets roughly double and add USD(2005) 424 trillion by 2100. Having CCS not available for the electricity sector but available in industry adds USD(2005) 34 trillion to the global policy cost. Having CCS not available in industry but available in electricity adds USD(2005) 175 trillion to the global policy costs; over five times as much as when it is unavailable in the electricity sector.

Table 5.1 Additional policy costs for reaching the 2°C target for different availability of CCS in industry and power/heat sectors compared to the case that all CCS options are available (allCCS)

	Annual climate policy costs [bln USD(2005)]		**Cumulative climate policy costs [tln USD(2005)]**	
	By 2050	**By 2100**	**Until 2050**	**Until 2100**
CCS only available for industrial production and fuel transformation, <u>not</u> for public electricity generation (CCS(IND))	+207	+952	+3	+34
CCS only available for public electricity generation, <u>not</u> for industrial production and fuel transformation (CCS(PUB))	+281	+6418	+5	+175
No CCS at all (noCCS)	+1470	+13898	+21	+424

6 Social and organisational aspects of CCS in industry

As CCS in industry is unlikely to displace investments in renewable power, it may be more acceptable from a “social licence to operate” perspective (Ashworth et al., 2010; Brunsting et al., 2011). The support of environmental organisations may affect the views of civil society as they tend to associate more closely with environmental organisations than with actors like industry or government (Huijts et al., 2007). CCS in industry still allows for some fossil fuel use and therefore does not deeply impact or alter the interests of the fossil-fuel industry, while still allowing for development of renewable energy in the electricity sector. This is partly demonstrated by the support for CCS from fossil-rich countries and international organisations (Coninck and Bäckstrand, 2011; Meadowcroft and Langhelle, 2009).

Given the structure of many industrial sectors, involving high-risk, high-revenue business models and a dominance of multinational companies with high technological capabilities all over the world, CCS deployment in industry is more achievable than in the more challenging power sector. This is especially the case in developing countries where there remains considerable growth in manufacturing and related industrial sectors. The potential for developing countries to move towards a “green industrial growth” paradigm is well supported through the smart use of CCS technologies. As an example, countries like China are already taking a leadership role in CCS generally (Liang et al., 2011; Zheng et al., 2011) – often in partnership with OECD countries or regions (e.g., Kalaydjian et al. (2011)).

7 Discussion and conclusion

Technology and general cost reviews, scenario analysis and indications of public resistance to CCS seem to suggest that application in industrial sectors is both cost-effective and necessary to keep global mean temperature rise within 2°C. Even if full decarbonisation in the power sector was completed, CCS in industry remains necessary if the Cancun climate target is to remain within reach. Developing economies will play a crucial role in this transformation. CCS in most industrial sectors benefits from technologies that are more readily available in the shorter term, have better cost reduction prospects, are able to effectively utilise CCS in hydrogen and bio-based synfuel production, and potentially have less objection from societal groups and competition from renewable energy options.
Additional policy costs to reach the 2°C target compared to a scenario with CCS available in all sectors are analysed to be around USD(2005) 34 trillion cumulatively by 2100 if CCS is not available in the electricity sector but around USD(2005) 175 trillion if CCS cannot be deployed in productive industry and fuel transformation sectors; over five times more. Not having CCS available at all has a much more dramatic effect on total costs (more than double the sum of the additional policy cost of CCS(IND) and CCS(PUB) combined) as it reduces flexibility to reduce CO_2 emissions in electricity, fuel and industry to a minimum. A possible consequence could be that the sustainability of biomass production will come under increased pressure.

CCS in industry is important and underrepresented in the CCS policy focus, but CCS in combination with biomass also plays an important role in all scenarios with CCS availability. This option, which is barely researched at all and not part of any of the large-scale demonstration programmes, warrants much more attention in order to hedge for climate responses in the longer term.

Much more can be done to include CCS as an option in green industrialisation policies in developing countries, in rapidly industrialising countries such as China and South Africa, but also in countries with lower levels of development but significant fossil fuel, biomass or fuel transformation sectors. Literature on industry policy (Rodrik, 2004) and technological innovation systems (Hekkert et al., 2007) suggest that in particular, supporting activities rather than whole sectors, creating an enabling environment and enhancing national capabilities are important, as well as bringing down costs in a global concerted effort. A combination of national industrial policy and international cooperation for CCS in industry is currently possible and more feasible than for CCS in the power sector. Without such actions, it is hard to imagine that CCS can be implemented globally or for greening industry in developing counties, which in turn would mean that attaining to climate goals will become difficult.

8 Acknowledgements

Heleen de Coninck, Tom Mikunda and Tom Kober acknowledge funding from the CATO2 project of the Dutch Ministry of Economic Affairs. The model-based analysis profited from research conducted under especially the LIMITS project. Tom Kober acknowledges previous work and feedback on this research given by B.C.C. van der Zwaan, H. Rösler and I. Keppo.

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