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Decarbonising industry in Sweden

an assessment of possibilities and policy needs

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Abstrakt/Abstract

Technical opportunities for a complete decarbonisation of the basic material industry in Sweden by 2050 are analysed. From this assessment, the report discusses policy implications for the industry sector given the overall framework set by the international climate negotiations.

Relying on current production systems and applying “end-of-pipe” solutions will be insufficient to decarbonise industry completely. Decarbonising the industrial sectors while maintaining production volumes requires a major effort to develop, introduce and invest in novel technologies and process designs that currently are not available on the market.

For achieving this, our analysis points to the need for complementing the current main climate policy approach of pricing the emissions via the EU ETS with a stronger policy for technical change. The support needs to include funding for RD&D but also for market development support in a broad sense. So far, this approach has worked well in the renewable energy sector through the use of various support schemes.

The report outlines a technology strategy for industry that identifies a set of broad technology platforms and infrastructure needs such as electro-thermal processes (e.g electrowinning), black liquor gasification, bio-based chemicals, magnesium based cement, and application of industrial CCS. All are in need of targeted support. Sectoral roadmaps for creating a common vision between government, industry and civil society are an important first step.

Another important part of a policy strategy towards decarbonisation is to clarify the long term reduction target of the EU ETS and how to deal with the risk of carbon leakage. This point to the necessity of widening the scope of climate policy to also include trade policy in the longer-term.

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Executive summary

In July 2011, the Swedish Government proposed developing a roadmap for attaining zero net emission of greenhouse gases by 2050. For most sectors in society, numerous visions for decarbonisation are available. However, visions for a complete decabonisation of the industry sector have been lacking in the policy debate so far. The aim of this report is to fill that gap and describe the potential technology systems necessary for a complete decarbonisation in a selected number of industries producing basic materials, including foremost the production of steel, cement, basic chemicals, aluminium, and pulp.

The report reviews the results from current climate-economic modelling and complements this with a technology assessment of the long-term opportunities that are not included in climate-economic models. The focus is on a complete decarbonisation. From this analysis, the report discusses policy implications for the industry sector given the overall framework set by the on-going international climate negotiations.

Relying on current production systems and applying "end-of-pipe" solutions will be insufficient to reduce emissions completely. Most estimates produced by climate economic models result in a reduction between -70 to -85% of CO_2 in 2050. Decarbonising the industry sector while maintaining production volumes requires a major effort to develop, introduce and invest in novel process designs that currently are not available on the market.

To completely phase out greenhouse gas emission in the industrial sector by 2050 is very challenging. Regardless of the specific numbers (zero or – 80%), by 2050 there will certainly be a need to develop the capacity to be "zero emission technology ready". By this, we mean that the technical systems necessary for a decarbonisation must be developed, demonstrated and commercially available for large-scale introduction in between 2040 to 2050. Once technical solutions are commercially available, it will still take many years before the technologies are widespread and common practice.

The report outlines a technology strategy for industry that identifies a set of broad technology platforms and infrastructure needs such as electro-thermal processes (e.g. electrowinning), black liquor gasification, bio-based chemicals, magnesium based cement, and application of industrial CCS. All are in need of targeted support. From this, the report also outlines a policy strategy for managing the inherent risks and difficulties in steering towards a long-term and complete decarbonisation of industry.

Our analysis points to the need for complementing the current main climate policy approach of pricing the emissions via the EU ETS with a stronger policy for technical change. Overcoming the numerous barriers for radical future technologies in the industrial sector, while at the same time managing the inherent risk of carbon leakage embedded in the climate change convention, requires a comprehensive policy package for technical development. Our analyses suggest that targeted support for specific technologies is necessary. The support needs to include funding for RD&D but also for market development support in a broad sense. So far, this approach has worked well in the renewable energy sector through the use of various support schemes.

Sectoral roadmaps for creating a common vision between government, industry and civil society are an important first step. The overall purpose of a roadmap may be to establish priorities on RD&D, co-ordinate various actors create networks for knowledge sharing, and map future technology and policy pathways.

Another important part of a long term policy strategy towards decarbonisation is to clarify the long term goal of the EU ETS and how to deal with the risk of loss of competitiveness and carbon leakage. Our analysis points to widening the necessity for widening the focus of long term climate policy to also include trade policy.

Background to study

To support the long-term climate ambitions adopted by the European Union, the commission launched a roadmap in May 2011 to assess the impacts and the potentials for reducing greenhouse gas emissions within the EU with 80 % to 2050 (EU COM 2011a). This roadmap is comprehensive and aims at covering the whole economy of the union. Since then, the commission has further developed a detailed roadmap for each energy sector in the union (EU COM 2011b). The EU commission encouraged member states to develop their own national roadmaps complementing the EU wide roadmap.

In July 2011, the Minister of Environment in Sweden took the initiative to develop a Swedish roadmap for attaining zero net emission for greenhouse gases by 2050. The ministry gave the Swedish Environmental Protection Agency (SEPA) the assignment to, in co-operation with several other agencies, develop a suggestion and analysis of how this could be feasible for Sweden and report this to the ministry by December 2012.

The EPA commissioned Lund University to write a report that would assess the potential for attaining zero emission in the Swedish industry sector with a special focus on the basic materials industry. The report will serve as a background for the SEPA and co-operating agencies (notably the Swedish Energy Administration) when developing their suggestions for the ministry.

The study has been written by Max Åhman, Alexandra Nikoleris, Lars J Nilsson at the Department of Energy and Environmental System Studies (EESS) at Lund University. A reference group consisting of Eva Jernbäcker and Ulrika Svensson from the EPA and Annika Persson and Malin Lagerquist from the Energy Agency (STEM), has commented on drafts.

The preliminary findings were presented on the 25th of May 2012 to industry representatives and the report has been finalised after taking into account their comments on the presented draft. Anna Ekman at EESS at Lund University has also commented on drafts

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1 Introduction

The long-term aim of attaining zero emissions in Sweden is ambitious and challenging. Visions for a complete decarbonisation of the power, housing and transport sectors exist with numerous details of technologies and changes that need to take place (IPCC 2007, IPCC SREEN 2011). In the agricultural sector, it is well known that emissions can decline substantially with good practices but that zero emissions are unattainable (due to e.g. methane and N_2O leakage from food production). However, the prospects for attaining very low or even zero emission in the basic industry sector have, so far, not been studied as much.

Assessments of the economically possible emission reductions in the industry sectors have indicated a potential reduction of 50 to 85% up to 2050. These reductions can be achieved with efficiency improvements combined with fuel shifts and adding carbon capture and sequestration (CCS) to the major exhaust stacks.

The aim of this report is to go one step further and describe and assess the potential technologies and systems for a complete decarbonisation and also to look at the potential for negative emissions. The time horizon is set to 2050 which allows and necessitates the exploration of technologies that currently are not technically or commercially mature and thus not well-represented in climate-economic models. From this analysis, the report discusses policy implications for the industry sector given the overall framework set by the on-going international climate negotiations.

This report is based on publicly available scientific articles, industrial and academic reports, and on the previous work within the department of Energy and Environmental System Studies in Lund, specifically the work within the LETS2050 programme (www.lets2050.se).

1.1 The UNFCCC and long-term targets for Sweden and the EU

Since the late 1980s, the Intergovernmental Panel for Climate Change (IPCC) has had the responsibility for assessing the scientific basis of human induced climate change. The results have gained increased international recognition and acceptance among business, government and the general public that major efforts to curb the threat of climate change are both environmentally necessary and economically wise.

The global policy response to the emerging scientific knowledge has been the establishment of the United Nations Framework Convention for Climate Change (UNFCCC). The UNFCCC was adopted in 1992 and states that the parties (195 national governments) should “prevent dangerous anthropogenic interference with the climate system“. At the time, the scientific understanding of climate change was still emerging and not clear enough for the parties to the convention to agree on any specific emissions or temperature level.

1.1.1 Global targets

However, science and the political understanding of climate science developed further and as a first step to fulfil the long-term objectives of the climate framework convention (UNFCCC), the parties adopted the “Kyoto protocol” in 1997. The Kyoto protocol is only the first step and has the goal of halting the escalating growth of greenhouse gas emissions by putting an absolute cap on emission for industrialised countries.

In 1996, the EU specified their climate goal by adopting a long-term target to limit the human induced global warming to 2 degrees above pre-industrial temperatures. Sweden adopted the 2-degree target in 2008 (Regeringen 2009). In December 2011, the parties to the UNFCCC in Cancun eventually adopted the 2-degree target on a global level.

Limiting human induced warming to 2 degrees is a very ambitious target and requires a long-term view on emissions reductions up to the year 2100 and beyond. According to the latest assessment of the IPCC (AR4), the 2 degree target implies that we need to reduce the *global* emissions of greenhouse gases by at least 50% to 2050 compared to the levels in 1990 and thereafter reduce the emissions to practically zero emission by 2100 (IPCC 2007)[1].

1.1.2 Mitigation targets for Sweden and the EU

The United Nations Framework Convention on Climate Change (UNFCCC) also includes a burden sharing principle that all signatories have a "common but differentiated responsibility" for reducing emissions. The burden sharing implies that industrialised countries should take a greater share of future emission reductions and that developing countries should be allowed to grow with fewer restrictions on fossil energy use and emissions.

In the Kyoto protocol, the burden sharing principle means that only industrialised countries are committed to decrease their total emissions and report this. Developing countries have no restrictions on their CO_2 emissions and are only committed to report on emission levels in a transparent and verifiable manner.

After 2012, when the Kyoto protocol ends, a new interpretation of the burden sharing principle has to be agreed upon. When and how much emission reductions fast developing and middle income countries (such as the BRICS[2]) should commit to after 2012 have been one of the primary obstacles for agreeing on a new climate treaty that could replace the Kyoto protocol. No conclusion has been reached yet. However, a decision was taken in 2011 in Durban to "adopt a universal legal agreement for climate change no later than 2015".

In the EU, the commission has interpreted the burden sharing principle in the convention that the EU needs to reduce its emissions by 80 to 95% by 2050[3] (EU COM 2011b). Some of these emission reductions could be purchased as "off-set" credits but the long-term availability of cost effective credits will be limited. Based on a review of scientific literature (EU 2011b), the commission suggests that at least a 77 to 80% reduction is necessary domestically within the union by 2050 and the rest (3% – 18%) can bought as off-sets. A similar long-term target to reduce emissions by 80% to 2050 was proposed in the US, the Waxman-Markey bill, but failed to get enough political support in 2009.

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[1] Later research has suggested that emissions need to decline even more rapidly as compared to the IPCC AR4, see e.g. UNEP Emissions gap report

[2] BRICS; Brazil, India, China and South Africa

[3] This implies that developing countries need to deviate 15-30 % from BAU in 2020 and start reducing their emission thereafter and return to slightly below their emission levels of 1990 (-5%) by 2050.

In Sweden, the government has proposed a long-term climate mitigation goal to achieve zero net emissions by 2050**.** However, the use of offset credits and carbon sinks (in Sweden mostly our growing forests) is not yet decided and could affect the domestic mitigation ambition substantially. Several other countries have also previously set similar or more ambitious long term targets for becoming carbon neutral, for example the UK, Germany and Denmark in the EU but also Costa Rica and Norway.

To completely phase out greenhouse gas emission in the industrial sector by 2050 is very challenging. Regardless of the specific numbers (zero or – 80%), by 2050 there will certainly be a need to develop the capacity to be "zero emission technology ready". By this, we mean that the technical systems necessary for a decarbonisation must be developed, demonstrated and commercially available for large-scale introduction in between 2040 to 2050. Once technical solutions are commercially available, it will still take many years before the technologies are widespread and common practice.

2 The Swedish basic materials industry

Our study focuses on the heavy industry in Sweden including the production of iron and steel , aluminium, cement, platform chemicals from refinery by-products, nitric acid, and paper and pulp. Mining is only briefly covered in chapter 5.3.1 due to the fact that most CO_2 emissions come from the large use of electricity (grinding, hoisting, pumps, ventilation, transport etc.), use of fossil transport fuels, heat for ventilation, etc. All these activities are deemed replaceable with renewable alternatives by 2050.

These industries are energy intensive. Not all have high emissions of CO_2 but all are sensitive to rising CO_2 prices/restriction as an effect of climate policy. These industries have also been considered for various specific treatments due to the risk of carbon leakage, notably the free allocation of emission rights (EUAs) within the EU ETS but also the in the early discussions of introducing “sectoral approaches” and border tax adjustment in the international climate negotiations.

Looking at the specific industrial sub-sectors assessed in this paper, they contribute roughly1,6 - 2 % of the Swedish GDP and directly employ 50,000 to 70.000 people depending on which subsectors you include (SCB 2012). However, including also the industry sectors surrounding the production of basic materials, the sector as a whole contributes to 7-8 % of GDP and employs at least 100 000. The heavy industry in Sweden uses 150 TWh energy per year (27 % of the total supply) and emits approximately 16,9 Mton (1/3 of the total) greenhouse gases (STEM 2011).

2.1 Trends and projections for emissions

In Figure 1 below, the historical emissions of CO_2 from selected industrial sectors in Sweden are given. The figure also includes the Swedish official forecast for emissions up to 2030. The forecast includes all measures for reducing Swedish emissions adopted up to June 2010.

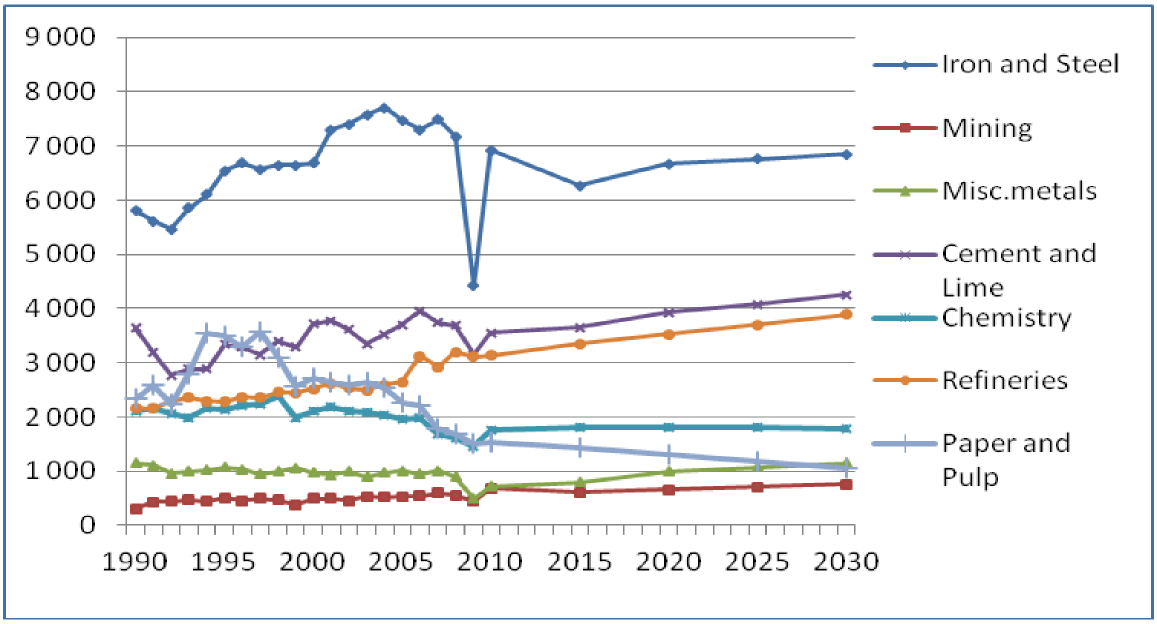

Figure 1 Emissions from Swedish basic materials industries. Source: EPA/STEM 2012

As can be noted from Figure 1, the emissions in the selected industry sectors do not decrease in the future but increases slightly up to 2030. This can appear to be contradictory to the stated climate ambitions in Sweden. However, the official projections do not control if set emission reduction targets are met domestically. The influence of the EU ETS (the dominant climate policy instrument for industry) is modelled as a static price signal (16 EUR/ton) on the margin (accounting for free allocation) and not as a quota restriction in volume. This is logical as the target for the reduction within the EU ETS is set on an EU level and not on a national level. Thus, in order to fulfil the overall quota restriction set by the EU, Swedish industry is forecast to buy allowances from either other sectors in Sweden or import allowances from Europe and emission reduction certificates from the developing world (CDM or JI).

Whether the predicted price of 16 EUR/ton CO_2 is a reasonable up to 2030 is uncertain, but it is the same carbon price projected by the EU COM in their reference scenario. Current prices are far below (< 10 EUR/tonCO_2). In the 2050 decarbonisation scenarios in the EU COM roadmap, the quota prices ranges from 25 EUR/ton in 2020 rising up to 104-370 EUR/ton in 2050 (EU COM 2011a).

2.2 Trends and projections for production

The total mitigation potential in the heavy industry sector relates strongly to the expected production growth. Future projections of emission growth are based on either projections of physical production volumes or projections of future growth of value added measured in economic terms. Regardless of which, the projections are based on the interpretation of observed historical trends.

2.2.1 Historic trends for production volumes

In Table 1, the basic production trends, as observed the last 20 years, are presented. The production trends of basic materials do not grow at the same speed as the economy in Sweden. This can partly be explained by a growing import of manufactured goods (embedded materials) and reliance on a less material intensive sector in the economy For some industries, a steady growth can be observed (notably the paper and pulp industry). The production volumes in the iron and steel and the cement industries follow different cycles in the economy. For the production of aluminium and ethane, the volumes have, or are set to, increase step wise due to new investments in capacity during the past few years.

Table 1. The trends in production volumes for basic materials in Sweden

	Trends since 1990
Cement	Swedish production of cement has fluctuated around 2 to 2,8 Mton cement/year following international building cycles
Primary aluminium	Swedish production has remained stable around 100 000 ton/year (maximum output at Kubal/Rusal). However, new capacity has recently been added to increase production to 130 000 tons/year
Iron and Steel	The production of steel has fluctuated between 4 to 6 Mton steel/year and the production of iron between 2,5 to 3,5 Mton/year following economic cycles. Since 1990, the production has increased 30%. However, viewed in a longer-term perspective, since 1970, the production has fluctuated.
Nitric Acid	The production of nitric acid for fertiliser has stopped in Sweden. Current production of 260 000 ton for use for technical nitrates has increased the last 3-4 years by 10% .
Ethene (cracker)	Since a major refurbishment 6 years ago, the production has slowly and steadily increased to around 500 000 to >620 000 tons of ethene/year in the cracker. Maximum output is currently 620 000 ton at Stenugsund and the remaining part is imported.
Paper and pulp	Production has seen a steady increase from 10 to 12 Mton pulp/year and from 8 to 11,5 Mton paper/year since 1990
Refineries	Production has changed during the last 15 years due to environmental considerations resulting in lesser demand for heavy fractions and higher demand for low sulphur fuels. Also, a shift from petrol to diesel has increased during the last 5 years. The domestic demand is stagnating but export of clean fuels is increasing.
Mining	Approximately 15 mines in Sweden are producing close to 50 Mton ore, of which 50% is iron ore and the rest non-ferrous ores, mainly gold, zinc, silver, lead, and copper. The last 10 years have seen an increase in prospecting for non-ferrous metals previously deemed unprofitable. With the notion of increasing global scarcity linked with a long-term increasing global demand, the mining industry sees a good potential for future growth

Sources: SCB (2012) complemented with personal communication with Yara and Borealis, Länsstyrelsen in Sundsvall, Miljöredovisningar from Heidelberg Northern Cement and Borealis.

2.2.3 Projections of production volumes

In Figure 2 below, the future projected production volumes for some of the basic materials investigated here are given. Figure 2 shows projections assumed by McKinsey (2008), the ADAM project (2009) and by the IEA (2010).

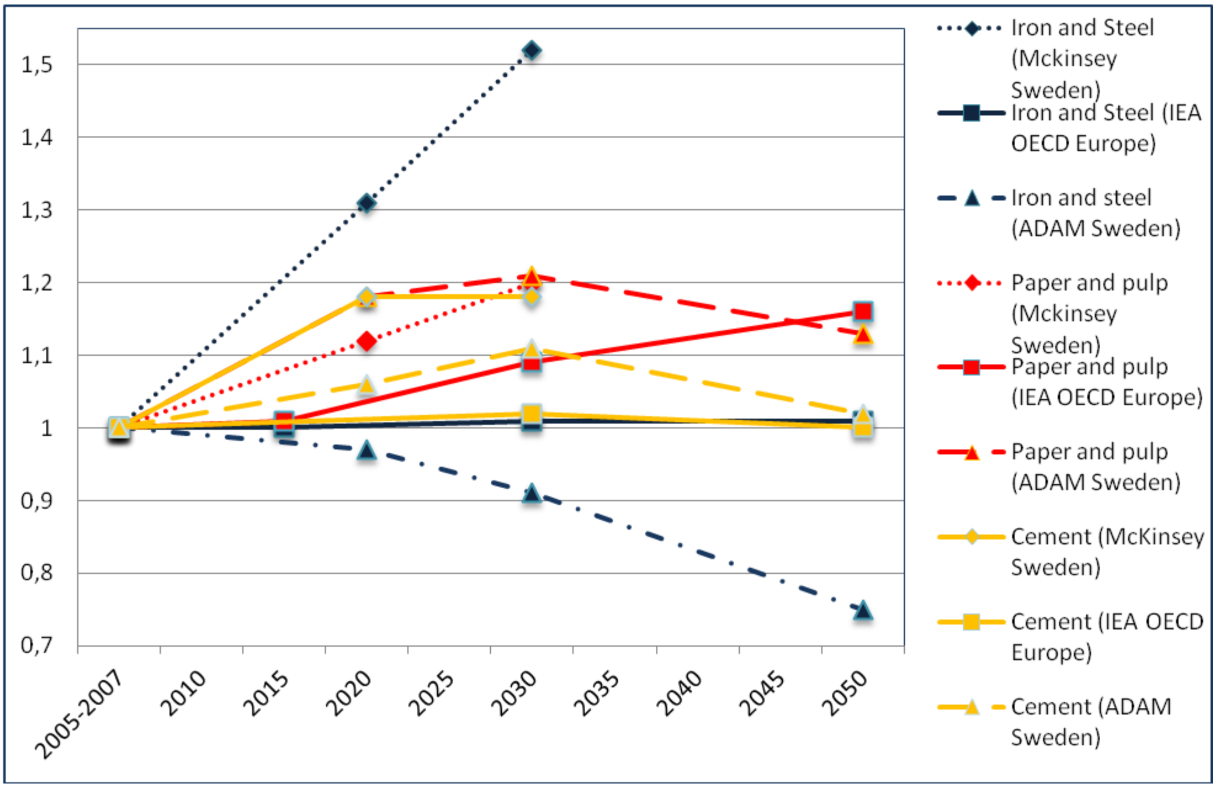

Figure 2 Production volumes for the Swedish & "OECD Europe" industry up to 2030/2050. Sources: McKinsey 2008, IEA 2010, ADAM 2009 (2-degree scenario)

However, as can be seen from Figure 2 above, the projections of McKinsey, the ADAM project and IEA differ substantially. The IEA assumes that production volumes in general will stagnate in EU and Sweden whereas McKinsey, based on trend extrapolation, assumes that production volumes in Sweden will continue to grow basically in line with the assumed GDP growth. The ADAM projections show a declining production of steel and a short-term increase of cement and pulp that declines in the long term.

The IEA projections are based on a general assumption, adopted by the OECD, that new production facilities will be located closer to the emerging markets. Production within the EU will concentrate on higher valued end products in the sectors facing global competition (as has been the case in Sweden for e.g. steel). Other sectors, such as cement, are assumed to follow the previous trends of regional/global cycles in the economy. The IEA further assumes that structural changes will make productions of primary materials grow less or not at all up to 2050 in the EU. The ADAM project assumes in their 2-degree scenario a strong push towards material efficiency resulting in less demand for basic materials (especially steel) in the future.

In conclusion, there seems to be an agreement that basic materials will not only be needed but also produced in the EU in 2050. However, the growth in domestic physical production volumes will be limited for most basic materials (see also IEA 2012). The building materials industry is projected to follow building cycles which are assumed to be quite stable the coming 40 years in Europe (no growing population and less economic growth). The aluminium industry is already "foot loose" in that the product has a high value and does not cost much to transport. High future global demand for materials will increase the price of virgin materials will increase the need and value for recycling[4]. Most projections also include an assumption of a growing reuse of materials in e.g. the steel industry, aluminium and basic plastics.

The general development assumption is thus that greenfield investments, investments in completely new industrial sites, are steered towards the emerging markets such as China, India, and Brazil.

2.2.4 Investment cycles for basic industry

The basic industry has a huge capital stock in existing processes. As capital is a scare resource for companies, the basic industry normally changes only gradually over decades. This existing capital stock can, to large degree, be regarded as a sunk cost, which needs to be considered when addressing the economics of technical change. The current industrial facilities within the EU (e.g. cement, steel, power and refineries) have an age structure where normally more than 70% of the facilities were commissioned before 1980 (Rootzén 2012).

Research on turnover rates for industrial capital stock reveals that, in general, there is no real fixed time limit for how long existing factories can run. New investments are typically done to increase production and to capture new markets and seldom are new facilities invested in with the sole purpose of increasing efficiency (Worrel and Biermans 2005). Existing investments will run until external pressure in to form of environmental legislation or excessive maintenance cost forces owners to close them down (Lempert et al 2002).

The notion that the EU will see little greenfield investment will have repercussions on climate mitigation options as a greenfield investment usually offers an excellent opportunity for introducing the best available technology. This is the case in many steel mills built in e.g. China today. If the EU instead will see more of retrofits/refurbishment in industry or brownfield investments (investments in existing sites), there will be an increasing need for assessing and understanding the economics and technical potential as this will differ compared to the economics and rationales of greenfield investments.

[4] It is uncertain if the current (2010-2012) high prices of virgin materials will last. Following a possible economic restructuring of e.g the Chinese economy we might see more moderate prices in the future.

3 Industry in climate –economic models

3.1 Top-down or bottom-up models

For assessing the future opportunities for mitigating emissions in the industrial sector, several different climate economic models are used. The use and design of models is always linked to the aim of using the model, i.e. what questions do you want answered? Models can be classified either as bottom-up or as top-down models.

Bottom-up models calculate the costs for individual technologies or technical systems based on what is known in terms of current and future costs and technical performances. These calculations can be done either with known technologies or with assumed future technologies. The term “cost” in bottom-up models usually refers to the direct technical cost for green investments or the incremental cost between a mitigation option and a fossil based option. Sometimes the term “societal cost” is used depicting a social discount rate, normally of 4%, has been used on the investment. The MARKAL model, developed and used by the International Energy Agency, is a good example of a bottom-up model. Other examples of a bottom up model are the McKinsey model for calculating a Marginal Abatement Cost curves (McKinsey 2008) and the Primes model used by the EU COM.

A top-down model calculates the total cost for the whole economy to reach a specific emission target based on measured or assumed relationship between economic output and energy/emissions. The term “cost” here refers to the economic loss of GDP that is the consequence of adopting a carbon price in a general equilibrium model. A top-down model includes economic feedback in the economy; e.g. if we invest more in wind power, there will be less money for investing in bioenergy. The EMEC model is an example of a top-down model used by the Swedish government. The EU COM uses the GEM E3M model and the OECD has developed the OECD-ENV Linkages model.

In the last ten to twenty years, several new energy-economic models have been developed specifically for assessing climate policy options. The most widely used models today are neither pure bottom-up nor top-down but rather hybrid models including both technical detail and a limited economic feedback. The largest and most complex use clusters of different types of models interactively combing top-down result to bottom-up sub-model for specific sectors. A typical example of the cluster approach is the models used by the EU Commission with PRIMES, POLES, GAINS and GEM E3M for assessing EU climate and energy polices and the ADAM project which uses a group of linked models including a detailed sub-model for industry.

3.2 Industrial representation in some well-cited models

The level of detail and ability to address specific industrial mitigation options differs between the models and also differs between the two basic types of models. Most long-term projections rely on bottom-up models/or sub-models.

In the PRIMES model used by the EU commission, industry is divided into twelve basic sectors and several subsectors totalling 26 different subsectors using the twelve generic processes. This gives Primes a very detailed technical description of industry compared to other models. However, despite the fact that Primes is usually regarded as a bottom up model, the key input is "added value" in economic terms[5] and not physical production volumes. Structural changes within industrial sectors are price driven; e.g. higher energy prices due to carbon restrictions will lead to more scrap-based aluminium or less primary aluminium, etc.

The IEA biannually presents the "Energy Technology Perspectives" (ETP) which contains detailed representation of industry and its emissions. The Energy Technology Perspectives is based on bottom–up modelling. Their model has extensive technical representation similar to the PRIMES model and uses endogenous assumptions regarding future physical production volumes and structural changes affecting in the heavy industry. Primes and ETP are similar in industrial and technology assumptions and resolution as they constantly exchange information and adapt to each other (EU COM 2011a).

McKinsey published a well cited bottom-up model that builds on identifying existing and novel technologies that can be expected within the time frame to 2030 and then calculating the costs for replacing incumbent technologies. McKinsey used a social discount rate of 4 % and assumed no implementation costs, no costs for "learning by doing", no legal barriers for e.g. co-generation, and that agents have perfect information and foresights of future technologies. With these assumptions McKinsey developed a set of marginal abatement cost (MAC) curves that received much attention, especially since they pointed out that there were numerous low cost abilities to reduce emissions. In these kinds of models, the ability to include advanced technological systems/changes is only limited to the actual knowledge of unproven technologies.

Top-down models such as EMEC and GEM E3M and OECD-ENV Linkages have far less technical representation of industry as they are driven by economic parameters derived from historical relationship between economic growth and energy use or emissions. However, top-down models can better simulate the economic structural changes between different industrial and other sectors of the economy, especially in the short and medium term, when one can assume that technical progress is less uncertain. Possibilities exist to adjust the historically derived emission intensities for accounting for assumed technical development. This is done for the Swedish official forecast where EMEC is complemented.

3.2.1 The competitiveness of future technologies

A key aspect is how to deal with the great uncertainty of future technology changes. Future technology costs are inherently difficult to predict with any accuracy but a number of methods have been used, e.g. the use of learning curves and long-term engineering cost estimates. Another very rough method has been to compare input cost of feedstock and energy and assuming that, in the long-term and with development, this makes up a similar share of total production costs.

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[5] The macroeconomic data on economic development and larger structural changes comes as input from the other models in the cluster such as the E3MG model.

For the use of learning curves see Neij (2008) or IPCC SREEN (2011). For an example of the use of engineering cost estimates for 2nd generation biofuels see Hamelinck and Faaij (2002) and Åhman (2003) for using all above methods for assessing of future vehicle technologies.

For the very scale dependent heavy industry, long-term estimates of emerging technologies are normally deemed too complex to give an acceptable estimate of (see e.g. Birat 2010, IEA 2011). However, within the ULCOS project, a cost tool assessment was made to categorise different solutions for strategic decision making. The general conclusion that can be drawn is that energy costs will be the major share of overall production costs regardless of route chosen (Birat and Lorrain 2006).

All future technologies in this report have been assumed to have the potential to become competitive in the future. These assumptions rest upon that technical development is successful and that enough investments are made in research and development of technologies which could also include early market introduction support via e.g. investment subsidies. Eventually, changing energy prices and policy induced higher prices for emitting CO_2 (mostly via CO_2 price but also via regulation) can make radically novel technologies competitive. However, we must acknowledge that all long-term cost estimates are fraught with uncertainty and this should be taken into account explicitly when interpreting model results.

3.3 Exploring future options with models and energy system analysis

Models deliver reasonable answers to questions posed given a transparently set of assumptions. Bottom-up models are typically used for *identifying cost-effective allocation of different mitigation technologies* whereas top-down models are used to *assess the macro economic effects in terms of GDP losse*s of proposed climate policies.

Most models do fairly well at projecting for the short and medium term as the input variables (econometric relationship for top-down models or technology costs for bottom up models) can be assumed with decent accuracy. However, several aspects need to be considered when trying to assess climate policy and mitigation options in the long-term.

For long-term planning purposes, we argue that bottom-up models have a greater chance of giving answers that are reasonable and usable compared to top-down models. However, bottom–up models also suffer from the fact that in order to calculate a future cost effective allocation of different technologies, the model needs, as input, reasonable reliable data on technical performance and economics. This limits bottom-up models to calculating the introduction and deployment of relatively well-known technical systems.

The focus of this report is on future technology shifts requiring systemic changes for a complete decarbonisation. This radical change cannot be represented in current climate-economic modelling. In this report, we complement existing model results with a long-term technology assessment approach. This allows us to describe and study more radical industrial and energy systems that could become carbon neutral or even carbon negative and provide technical insights into strategic development needs and specific barriers. Also, it can increase the knowledge of future modelling and better prepare anticipated but historical unaccounted effects such as relative price changes.

4 A review of model results in the medium and long-term

4.1 Assessment of the Swedish potential up to 2020 and 2030

Assessing reduction opportunities up to 2020 and 2030 is, in a climate change context, regarded as short to medium term reductions. In the time frame up to 2020, it is reasonable to assume that the best available technologies currently will be phased in and that some of the technologies currently being researched and demonstrated will have begun, given successful development, to penetrate the market on a commercial basis. The major effects on emission reductions up to 2020 will be the phase-in of the best currently available technologies. The potential emission reductions modelled with bottom-up models up to 2020 can thus be based on relatively strong assumptions.

Assessing the potential up to 2030 allows for assuming successful development of currently demonstrated/early market technologies, i.e. technologies that still can relatively clearly be defined in terms of future costs and potential to reach market maturity. Up to 2030, emerging technologies currently in the demonstration phase could have a substantial impact if the introduction to the market begins before 2020. In Table 3, we present two bottom-up studies for identifying which technologies that are assumed and evaluated, the “Kontrollstation 2008” (SEPA 2007) and the McKinsey study for Sweden (McKinsey 2008).

Table 3. Abatement technologies and the potential reductions up to 2020/2030

	Iron and steel (incl. mining of ore)	Cement and lime	Paper and Pulp	Refineries and petrochemicals
Abatement technologies assessed to 2020	Fuel shift coal/oil to n-gas for mining Replace coke with coal in steel BOF furnace Cont. efficiency via heat integration, pre-heating of scrap, process optimisation	Replacing oil with biomass in furnace Cont. energy efficiency improvements (fuel) Reducing clinker content by using ore e.g. slags, ash.	Replacing oil with various qualities of solid and liquid biomass. Efficiency and heat integration which could lead to export of electricity	Not assessed by SEPA in detail Heat recuperation Process optimisation Internal power production
Abatement technologies assessed up to 2030	CCS assessed by McKinsey at cost of 400 SEK/ton	CCS assessed by McKinsey at cost of 400 SEK/ton	Impulse drying McKinsey identifies 1, 54 Mton red. but at costs between 1000-2000 SEK/ton	Feedstock integration refineries/petrochemicals. CCS assessed by McKinsey at 400 SEK/ton
Reduction compared to BAU	6 - 8% 2020 < 45% (max) 2030	2- 10 % 2020 < 20% 2030	16 - 30% 2020 16 - 60% 2030	< 2,4% 2020 < 80% 2030

Sources: McKinsey 2008 and SEPA 2007. No separate estimate on reductions potentials for mining of non-ferrous metals and aluminium were made.

SEPA (2007) assessed the economically potential up to 2020. The mitigation options often came at a price below 100 SEK/ton CO_2 but also included some opportunities up to 400 SEK/ton as optional. McKinsey (2008) assessed opportunities up to 2030 and at a marginal lower than 500 SEK/tonCO_2.

In the iron and steel industry there are no major shifts in technology, up to 2020 or 2030, that are deemed possible. Thus, the mitigation potential is relatively small. In the cement sector, the reductions are of similar magnitude and a result of mainly energy efficiency improvements and the reduction of clinker content in the cement. Paper and pulp are assumed to have a higher potential for reducing their emission despite the fact that they have already relatively fossil free. The opportunities come from phasing put parts of the remaining oil used for heating and for continued heat integration resulting in less heat demand. Refineries are not assessed in detail by SEPA , but McKinsey sees small opportunities in the short term and substantial opportunities in the medium term with the introduction of CCS.

CCS is not seen as a possible mitigation option before 2020. McKinsey uses a breaking point of 500 SEK/ton CO_2 abated when assessing opportunities. In their opinion, this leaves out CCS before 2020, as the costs will be between 590 – 780 SEK/ton CO_2 by then. However, by 2030 McKinsey assumes that the cost for integrating CCS into current processes in cement, steel, and refineries will have decreased to 400 SEK/ton CO_2 and thus be implemented where possible.

In general, the technologies assessed in Table 3 above are all well-known or predictable. The total mitigation potential is limited only by assuming the introduction of new technologies where they are easily integrated into existing industrial production processes.

4.2 Mitigation in the long term – model results for 2050

Relatively few models have assessed the mitigation potential and the related economics for attaining very low emission levels in the long-term (2050).

On the international level, the biannual IEA publication “Energy Technology Perspectives” (ETP) is one of the most well-known models with both industrial and technological details and a long-term view (2050). On the EU level, the detailed bottom-up modelling with the Primes-model, which also has details on a national level, is used by the commission for formulating policy proposals, e.g. the EU low carbon roadmap. The EU funded ADAM-project built a cluster of models including an industry specific sub-model that contains results on both national and on an EU level. On a Swedish level, IVL (2010) and Åkerman et al (2007) have, with varying details on the industrial sector, shown what a low carbon society might look like in 2050.

In Table 4, an overview of these long-term assessments is given. The technical details are, given the long time frame; presented on a general level and not per industrial subsector. This level of detail would only be possible with the ETP and the ADAM project.

Table 4. Reduction potential and basic technologies used for a selection of models

	Reduction in industrial sector compared to 1990	Technologies
ETP 2010 (OECD Europe)	Reduction in all sectors: 70-80% Reduction in industry: 66%	Efficiency and recycling (42%of red.), Biomass replacing fossil fuels where possible (18%). CCS the major contributor for reduction in heavy industry (40% of red.).
EU COM (EU27)	Reduction in all sectors: 80% Reduction in industry: 83- 87%	Efficiency, Biomass, CCS the major contributor in the long term. low introduction of bioplastics, etc.
ADAM 2C scenario (EU 27)	Reduction in all sectors: 78% Reduction in industry: 65%	Efficiency, CCS in steel and cement, solar heating + general dematerialization resulting in less production
IVL (Sweden)	Reduction in all sectors:79% w CCS, 72% w/o CCS Reduction in industry: 53% w. CCS, 36% w/o CCS	Efficiency (3,45% per year red.) Biomass replacing all fossil fuels except for propane. CCS for easy accessible process emissions in steel and cement
FMS /SU (Sweden)	Reduction in all sectors : 85% Reduction in industry: unclear. Some fossil energy left for steel processes.	Efficiency(25-35% less energy demand by 2050), Biomass in industry (50% of energy), limited availability of CCS for process emissions assumed

Sources: ETP (IEA 2010), IVL (IVL 2010), FMS/SU (Åkerman et. al 2007), EU (EU COM 2011), ADAM (2009).

All the long-term assessments come to the conclusion that an overall reduction of 70 to 85 % is possible to 2050 with technologies that currently can be assessed and at a reasonable cost. For the industry sector, most models calculate a slightly lesser decarbonisation between 55 to 66 % to 2050. All these assessment have in common that they assume approximately the same technologies as mentioned in the assessments for 2020 to 2030 in Table 3 but with higher introduction rates. The technologies used at larger scale in 2050 are the technologies being demonstrated today and that are deemed possible to predict future cost and technical performance.

General efficiency gains are a major contributor to mitigation also in the 2050 scenarios. All studies identify an "efficiency gap" that will help keep total energy use at the same or lesser level as compared with today by 2050. As an example, current Best Available Technologies will probably be completely phased in by 2050 resulting in up to 28 % reductions according to ETP (IEA 2010). The potential efficiency gain is also linked to increased recycling of materials (e.g. steel, and plastics) to keep energy use down.

Biomass offers CO_2-low energy supply options in all sectors. The extensive use of biomass is given a major role as it is assumed to directly replace a substantial share of fossil energy. Biomass is expected to replace most oil and coal and eventually natural gas in industry for heating. Some cases (IVL 2010) also assumed bio-coke to utilised as reduction agent in steel making

CCS is included in the models and is seen as a major contributor for reducing emissions after 2030 by most models. For ETP (IEA 2010), up to 40% of the reductions are attributable to CCS.

McKinsey (2008) assumes a major introduction of CCS by after 2020 at a cost of only 400 SEK/tonCO_2. The EU COM also assumes an introduction of CCS after 2025 at the cost around 30 EUR/tonCO_2. However, CCS is generally modelled as an “end-of pipe solution” targeting only the easy accessible CO_2 exhaust gas streams from high purity industrial sources like hydrogen production in refineries, natural gas sweetening, or by applying post-combustion capture technologies for mitigating a share of the total emitted CO_2 from blast furnaces or cement kilns.

Novel technologies, such as heating with electricity or various hydrogen pathways, which would require either major development efforts or redesigning of new industrial processes concepts, are described only in the ETP 2010 and more in ETP 2012 (IEA 2010, 2012) but not deemed possible to asses in the model. However, ETP 2012 stresses the need for a set of core technologies such as electrowinning in the steel sector, novel low-carbon cements and hydrogen in the chemical sector as to be developed in order to attain near zero emission by 2075 (IEA 2012).

5 Decarbonising industry - general technologies

Changes in current technology systems will not always suffice to decarbonise industry and reduce energy or process related emissions completely, as seen above in Table 4. Systemic changes in the production processes of basic materials are needed for a complete decarbonisation of these industries. These types of radical changes have not been represented well in climate-economic models.

Below, we analyse emerging technology options with a focus on what is necessary for a *complete* decarbonisation of industry. Some presented technologies presented are deviating substantially from current production systems whereas other technologies are already being used in industry. However, together these technologies could make Swedish basic industry completely decarbonised

In chapter 5, we present general technology systems that will be required for most of the suggested solutions to a decarbonised industry. In chapter 6, we address specific opportunities for each industrial category.

5.1 Industrial heating

In Sweden approximately 37 TWh of fossil energy is currently used in industry (STEM 2011). Approximately 18 TWh is coal and coke that is used mostly in the iron and steel industry along with pelletising in the mining industry. The remaining 19 TWh is oil products, propane and natural gas that are mostly used for heating purposes and to some extent as internal transport fuels.

The most obvious way of reducing CO_2 emission from fossil fuel combustion for heat production is to replace fossil energy with biomass. The replacement of oil and coal to biomass is the common suggestion in climate-economic mitigation studies in Sweden (see. e.g. IVL 2010, McKinsey 2008, SEPA 2007). As an example, IVL 2010 suggests that almost all-fossil energy use in industry could be replaced with biomass. The IVL 2010 scenario retains only some propane gas used for cutting in the industry and coke for iron ore reduction.

Bioenergy for heating purposes is technically relatively easy to use either as solid biomass in adapted furnaces or as methane gas injected into the natural gas grid. However, for several applications in e.g. lime or cement kilns and for blast furnaces, there is a need for pre-treating the biomass into a more homogeneous and energy dense energy carrier. Development is needed and underway for different variants of e.g. biochars, biocrude or bio-oils produced via pyrolysis, hydrothermal upgrading (HTU) or flash pyrolysis. Supplying bioenergy in the form of biomethane is an option for replacing natural gas.

The supply of sustainable grown biomass will be limited in the future but at what level is still heavily debated. There will be many sectors competing for biomass resources. The “non-biomass” options for decarbonising industrial heating are either direct solar heating or to use electricity for heating. CO_2 free electricity can be used for decarbonised heating via direct resistance heating, via heat pumps or via a range of electrothermal technologies.

Solar heating via solar collectors is globally a major opportunity for industries with low temperature process heating needs such as the food and tobacco industries, textiles and leather industry, etc. Today, solar heating systems provide industrial heat up to 120 °C. Technically, industrial systems are being refined and developed to provide solar heating up to 250°C. By using concentrated solar collectors (CSP) it is technically possible in the future to produce steam at temperatures above 1400 °C. However, solar heating have so far has not managed to penetrate the Scandinavian market in industrial applications due to cost and technical considerations.

Heat pumps are already used in industrial applications in Sweden, open systems for steam pumps (ångkompressorer) in the paper and pulp industry and closed loop heat pumps in some applications as well for low temperatures (below 130 ^{o}C) (Wallin and Berntsson 1994). Current use of heat pumps for higher temperatures has been limited by the lack of suitable refrigerants. However, development is underway and high temperature heat pumps are currently tested for temperatures of up to 300 C (IEA Heat pump center 2012).

Electrothermal technologies that generate electromagnetic radiation, e.g. heating via microwaves, infrared radiation, radio waves, ultra violet light, induction, and electron beams, are currently being used where there is a specific need for exact and well controlled temperatures and temperature gradients. Electrothermal technologies have the potential of being efficient as they can heat a very specific area without heating the surrounding material as is the case with conventional convection heating. Some electrothermal technologies heat only the surface (such as infrared radiation) whereas others specifically penetrate the materials and heat the volume (such as microwave and radio frequencies). Induction heating has the potential to heat just the connected material. Examples of current use of electrothermal technologies for heating are in the food industry for drying and in the automotive industry for coating, curing paints, etc.

Plasma technology is also an electrothermal technology that has since long been used for steel production from scrap (electric arc furnaces). Paper drying is also an area where the use of electricity in infrared dryers could increase and replace gas fired dryers and electric impulse drying could increase overall efficiency. EPRI (2009) gives a comprehensive overview over future potential applications for electrothermal technologies.

5.1.2 Heat profile in industry

The selection of different technologies for decarbonised heat in industry is dependent on the temperatures used. Process heat is commonly divided into low temperature heat below 100 °C, medium temperatures between 100 and 400 °C, and high temperatures between 400 up to over 1400 °C (e.g. steel making, cement calcination).

Comprehensive numbers on heat demand in Swedish industry divided upon temperature ranges do not exist so any detailed assessment of the potential cannot be made. However, Figure 3 gives the estimated temperature ranges for the heat demand in Swedish industry. The calculations are based on a German in-depth study which was extended and adapted to Swedish conditions for producing the estimate.

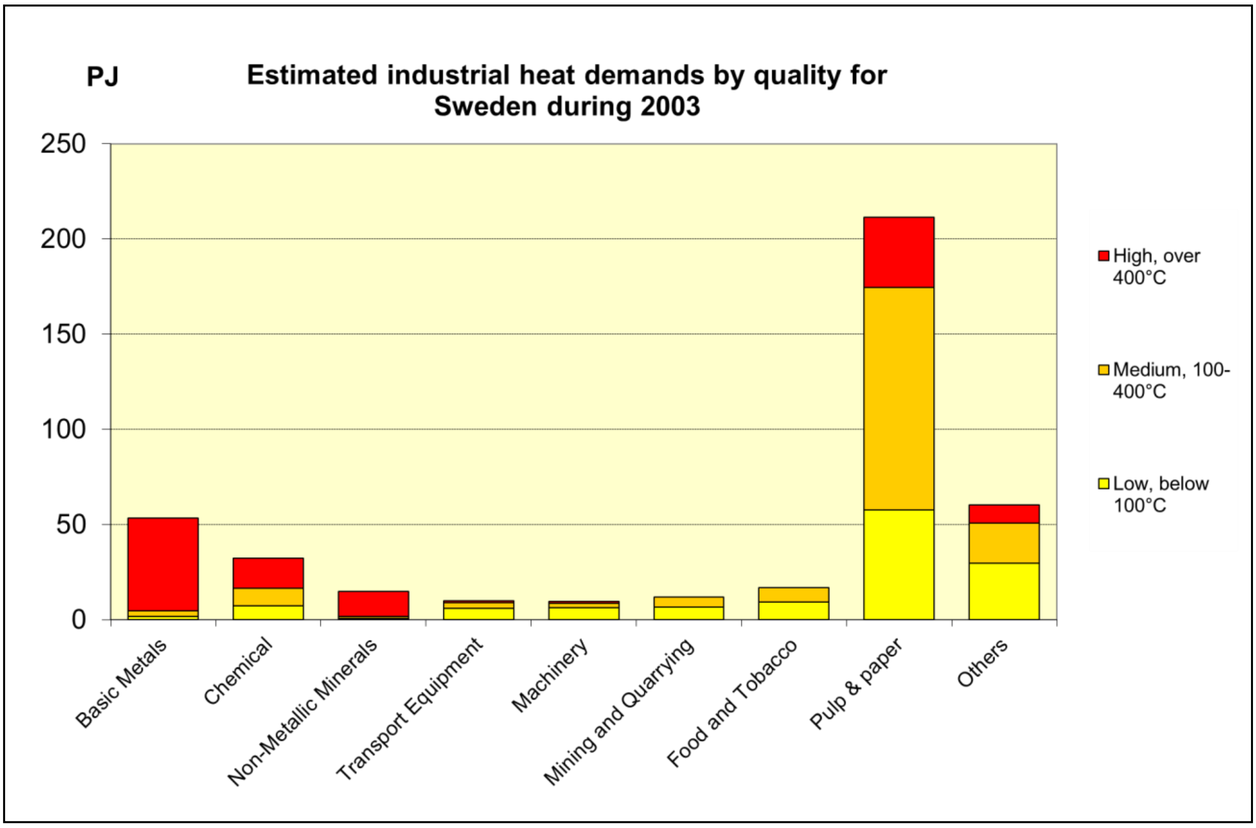

Figure 3 Estimate of temperature demands in Swedish industries 2003. Source: (Werner 2012)

For temperatures below 100 C, both heat pumps and solar heating have the technical potential to supply heat. However, most industries in Sweden have a surplus of low temperature heat (spillvärme) which has resulted in a growing export of heat for district heating systems (currently 5,9 TWh).

The future potential for heat pumps and direct solar heating in industry can be found in the temperature range between 100 to 400 °C. Development of efficient closed loop heat pumps that can deliver these temperatures are under way (e.g. development of refrigerants). On the basis of the original heat profile in the German study, Rainer (2010) found that 16% of current heat demand in Germany could be met by heat pumps [6].

At higher temperatures above 400 °C the already existing electric arc furnace and alumina smelting can be decarbonised if electricity supply is CO_2-neutral. In the future, plasma, induction technology and also concentrated solar power (CSP) can produce heat above 1000 – 1400 °C.

In Sweden, the major industrial users of heat are the paper and pulp industry and the steel industry. The iron and steel industry needs temperatures of 400 - 1400 °C and the paper and pulp industries has a surplus of low grade heat that could partly be upgraded to higher temperatures

6 In the same range, solar heating also has potential. Solar heating has begun to find niche markets in Northern Africa and Southern Europe where solar radiation make this technology economic viable in contrast to Northern Europe. A study estimated the potential that 3-4% of industrial heat demand could be supplied by solar heating in central Europe (Rainer 2010).

with by heat pumps (see Bengtsson and Berntsson 2002). Other industries that might be appropriate for heat pumps or solar heating in Sweden are the food, brewery and tobacco industries which consume 0,7 TWh of oil and 1,5 TWh of fossil gas, mainly for heating purposes. A major part of this industry is located close to the natural gas pipelines in Sweden, which explains the high use of fossil gas and could act as a barrier for introducing other heating systems.

5.2 Industrial Carbon Capture and Storage (CCS)

Carbon capture and storage (CCS) of emitted CO_2 has, during the past ten years, been seen as the major contributor to radical reductions in the long-term. CCS systems are currently operating in industrial applications such as gas desulphurisation, e.g. in Norway and Algeria.

The analytical focus has mostly been on understanding how to capture CO_2 from the flue gases of the power sector, see e.g. IPCC (2005). Less analytical attention has been directed towards CCS in industrial applications. UNIDO and IEA have recently begun to explore and assess the applicability of CCS into industrial facilities (UNIDO 2011).

5.2.1 Capture of CO_2 and integration in industrial applications

The cost and potential for applying CCS in industry depends on the concentration of the gas stream(s) and on the ability to integrate capture technologies in the process. In current climate-economic modelling, CCS is projected be introduced and retrofitted to current industrial applications some time beyond 2025. Some industrial processes are very suitable for capture as the gas leaving is almost 100% pure CO_2, such as ammonia production and natural gas processing (so-called high purity sources). High concentration is a major benefit as you only need to clean and compress the gas to pipeline specification for further transport.

The current systems for CO_2-capture from low concentration flue process gases are chemical absorption, physical separation in membranes, cryogenic separation or pressure swing absorption. These capture systems only capture between 85 to 90% of the CO_2 in the diluted flue gas (IPCC 2005)[7]. To capture close to 100% of the CO_2, the industry needs to produce a close to pure CO_2 stream in the process. This can be achieved either with oxy-fired streams or pre-process removal. It can also be called in-process CCS. In oxy-fired processes, pure oxygen is used instead of air in the combustion process. Thus, the flue gas is not diluted with the inert nitrogen from the air. In pre-process capture or in-process removal, the CO_2 is separated as a part of the process, e.g. in gasification of biomass/coal or in gas desulphurisation. These novel technologies have the potential to increase the capture close to 100% of the CO_2 (UNIDO 2011).

Some industrial applications represent the “low hanging fruits” of CCS, as is the case with natural gas desulphurisation in Norway and Algeria or enhanced oil recovery (EOR) in the US, where the CO_2 can be captured in a relatively pure form directly from the process or has an added value (e.g. EOR). In most industrial applications however, integrating CCS will be far more complicated

[7] Coupled with the increased energy demand for regeneration of the absorbent, the life cycle emission reductions are typically around 80-85% (IPCC 2005).

where major process changes will be necessary in order to capture a substantial part of the emission (UNIDO 2011).

For major industrial emitters like steel and cement, the concentration of CO_2 in the flue gas stream can be relatively high (between 20 to 40%) as compared to power production (3-14%). However, in industrial applications there are usually several point sources of CO_2 emissions within the same site with varying concentrations and flows. As an example, an integrated steelwork often emits CO_2 from ten different smokestacks with differing concentration (Birat 2010). Capture system also require energy for either regeneration of the absorbent, for pressurising, cooling or for oxygen production. Some industrial applications might have the benefit of excess low-grade heat that can be used directly, or via heat pumps, to regenerate the absorbents if chemical absorption is the preferred capture solution.

Targeting full capture of all emissions using advanced oxy-process or pre-process removal designs requires substantial changes to the whole industrial process in respective industries. Several options for redesigning the process and integrating CCS as a part of the new process exist for both the cement and the iron and steel industry. In the cement industry, manufacturing cement with pure oxygen in the process has been suggested and is currently being researched. However, the few CCS-demonstration projects under way in the cement sector are all based on standard post-combustion technologies (Mott McDonald 2010). In the steel sector, ULCOS presents several options that include partial or full capture of CO_2 integrated into new process designs. One concept that enables retrofitting the existing blast furnaces, is the ULCOS TGR-BF concept[8], with the potential to capture 65 to 75 % of CO_2. This has been tested in Luleå. ULCOS have also another concept that requires a complete new greenfield facility, the Hlsarna concept, which can capture over 80% of total emissions (Tata 2012). This concept will soon be tested in small scale in the Netherlands.

In the paper and pulp process, there is a good opportunity to use CCS in combination with future black liquor gasification. As the CO_2 would be separated in the gasification process the capture of CO_2 would be relatively easy. If the black liquor is based on biomass, the net emissions would be negative. How negative depends upon whether black liquor gasification result in hydrogen or F-T diesel/methanol as a fuel.

5.2.2. Transport and storage

Transport of CO_2 is well proven and normally seen as unproblematic. Transport represents only a minor part of the total cost of installing a CCS system. In an example from West Sweden, the calculated transport cost is around 12-14 EUR/tonCO_2 (CCS in the Skagerack/Kattegat 2012).

Storage is also tested in a smaller scale and exploration of future possible storage sites has been given much attention within the EU and Sweden. In Sweden, this responsibility lies with the SGU (Swedish Geological Survey). Two projects have been conducted to study the potential of storing

[8] TGR-BF: Top Gas Recycling – Blast Furnance. A “breakthrough technology” developed within the ULCOS consortium

CO_2 in the Baltic, Östersjöprojektet (VTT 2010) and in the Skagerack-Kattegatt region (ccs-skagerackkattegatt.eu).

In general, there seems to be suitable potential storage capacity in the south of the Baltic and in the Skagerack region. They are all within a reasonable distance from major emitters (cement in Gotland, steel in Oxelösund on the East coast and the refineries and the chemical cluster in Stenungsund on the West coast). For the steel manufacturing plant in Luleå or the pulp and paper mills along the Northern Swedish coast, the distance to suitable storage capacity is longer and might require transport by ship. However, further testing is needed before these storage sites can be approved. Outside Norway, there are major fields that currently have been tested and deemed suitable and is currently used for CO_2 storage.

5.2.3 Energy demand and costs for CCS

Applying CCS could increase the energy demand. In power production, the use of current available capture technologies, chemical absorption, will result in a 10 to 40% loss of overall efficiency accounting for the extra heat and electricity need (IPCC 2005). The energy losses come mostly from the extra heat needed for regeneration of the absorbent but energy is also needed for compression of the CO_2 to enable transportation and injection into storage.

For currently used methods of chemical absorption and regeneration there is a heat demand for 2,7 to 3,3 GJ/tCO_2 captured and an electricity demand of 0,06 to 0,11 GJ/tonCO_2. A further 0,4 GJ/tCO_2 compressed to 110 bars for transport is needed (IPCC 2005). However, the low-grade heat needed for regenerating the sorbent can in some cases be found as excess heat within the facility. As an example, retrofitting CCS to a craft pulp mill would only need 1,45 GJ/tonCO_2 additional as the rest can be utilised from excess low grade heat within the facility (Carbo 2011). In an integrated paper and pulp mill there would be less excess heat available (ibid.).

New capture technologies will change the extra energy demand needed. Oxy-fuel capture requires energy for oxygen separation and compression and will require 200-204 kWh electricity per ton CO_2 captured and substantially less heat compared to chemical absorption (UNIDO 2011). For cement production, the extra energy demand for oxy-fuel capture is estimated to 90 to 100 MJ of low-grade heat/ton and 110 to 115 kWh/ton of clinker produced (Mott McDonald 2011). For pre-combustion, the CO_2 is usually separated as a part of the process and thus allocation of this energy is not straightforward. However, there will still be CCS specific energy needs in the form of compression and transport of the CO_2.

The introduction of “normal” CCS is assumed to cost between 50 to up to 150 USD/ton CO_2 avoided in year 2025 to 2030 (UNIDO 2011, McKinsey 2009) depending on which industries and successful development. Closer examination in the CCS-Skagerack consortium ended up with figures around 67 to 86 EUR/ton (CCS-SkagerackKattegatt 2012). The costs of redesigning the process and capture “in process” CO_2, such as Hlsarna, are varying and deemed too unreliable to be included in any climate-economic modelling (Birat 2010, Mott McDonald 2011).

CCS can play an important role in the future low carbon society in Sweden. However, in order to attain really deep emission cuts down to zero emission or negative, the CCS alternative requires substantial redesign of industrial processes and this requires development and will take time.

Retrofitting CCS to industrial applications means that (i) capture will be done only at the major smoke stacks at the industrial site and (ii) that current mature post-combustion technologies such as chemical absorption or future membranes are used. Applying CCS in this way could reduce emissions up to 65 to 85 % for steel and cement plants (Birat 2010, Mott McDonald 2010). Adopting CCS to industrial applications does not seem to be the same kind “end of pipe“ solution as for power production. Costs for industrial CCS are also generally regarded as higher compared to CCS in the power sector if you exclude the low hanging fruits of high purity sources. On the other hand, if processes are redesigned anyway, this represents an opportunity, e.g. introducing black liquor gasification, where the additional costs for introducing CCS could be less.

5.3 Industrial electrification

In this report, we have assumed that the power sector is totally decarbonised by 2050. The versatility and efficiency of electricity as energy carrier motivate the increased use of electricity in industry. The path forward to attaining a zero or close to zero emissions in the power sector is relatively well known and includes several different supply options. The mostly domestic power sector also faces less political challenges in terms of competitiveness compared to the global industry sector. It is well accepted that there is a major opportunity for several emerging zero emission power technologies, such as solar photovoltaic, concentrated solar power, on- and off-shore wind power, biopower etc., to become cost competitive within the next eight to fifteen years (IPCC SRREN 2011). The EU energy roadmap (EU COM 2011) decarbonises the power sector almost completely and the IEA shows in their perspectives the same opportunity (IEA 2010).

Current power prices in the Nordic electricity market are low compared to central Europe. However, with increased integration of power system across Europe, the prices of electricity will become more like the prices of electricity in Europe (i.e. higher). In a decarbonisation scenario, industrial producers relying on grid based electricity will pay the cost of long term marginal CO_2 free production. An upper limit of this average long-term cost could be the cost of large-scale introduction of solar cells. Current long-term estimates give a possible production cost of 0,2 to 0,5 SEK/kWh in 2050 (IPCC SREEN 2011, IEA 2012) which indicates that future renewable electricity prices *need not* be substantially higher compared to today. The Swedish conditions make it more probable to be in the higher price range. However, medium term estimate usually shows substantially higher prices for large scale introduction of renewable power and substantial early investments via e.g. feed-in tariffs, certificates, CO_2 prices etc. are needed for gaining experiences and reducing production cost in line with the assumed learning curve.

The way the introduction of renewable electricity is supported and the way the electricity market is regulated has a strong effect on the price, the price volatility and ultimately on the competitiveness of electricity intensive industries. With current marginal pricing of power, the extra cost of the EU ETS emission quota is seen directly on the electricity bill for industry. Within the EU there is, however, a possibility for the member states to compensate electricity intensive industries for this price increase. In the support mechanism for renewable electricity in Sweden (the quota-based “certificate” system), the industry is exempted and the incremental cost (the certificate price) is only paid by household consumers. The balance between decarbonising the power sector with a high CO_2-price or via targeted subsidies for renewables will thus have a great effect on the basic industry.

5.3.1 Industrial sectors reliant on electricity

The production of aluminium is today very electricity intensive and sensitive to the power market. The global aluminium industry is already regarded as “footloose” industry seeking new investments where they can find low cost electricity. This usually means either oil producing states with regulated and/or subsidised markets or developing countries with poor transmission lines and large amounts of “stranded energy” e.g. hydropower or remote gas.

The mining industry is also very dependent on the power sector. The total electricity use for extracting non-ferrous metals was 0,8 TWh in Sweden in 2004 (ÅF 2007)[9]. The non-ferrous metals mining sector uses electricity for hauling, hoisting, pumping, air circulation fans, and transportation. Apart from the large use of electricity, the mining of non-ferrous metals also needs liquid fuels, diesel, for trucks and heat that is either supplied via e.g. oil furnaces or sometimes purchased. Replacing diesel and heat with renewable alternatives cannot be regarded as technically challenging in the longer term. Continued electrification of transport and heat demand via e.g. transporters and heat pumps, is seen as strategic for a number of reasons in the mining industry (health, productivity etc.). However, this will increase the mining sector’s dependence on the power market. As the mining associations usually point out, the price of power is a major share of production cost, often in the range of 15 to 20% of total costs, and fluctuates more than the price of their end products. The mining sector in Sweden has developed a vision for 2030 and beyond in which they integrate the aim for reduced emissions and future energy use with workers safety, better materials use and automation (Rock Tech Centre 2011).

Electricity has again become a much more strategic issue for industry compared to the last fifteen years of selling industry-owned power production facilities as an effect of the deregulation of the power sector. Already, we see a shift in attitude again, in e.g. the paper and pulp industry in Sweden, towards reversing this trend and integrating power production as a core business (Ericsson et al 2011). The access to and demand for future decarbonised electricity will become a much more strategic issue for basic energy intensive industry such as the mining industry, aluminium industry and the steel industry as future consumers and e.g. the paper and pulp industry as future producers. As an example, future steel production could become one of the single biggest consumers of electricity if they move away from reduction with coke towards electrowinning which we examine in the next chapter.

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[9] More specific statistics on the non-ferrous mining industry are not available in the official statistics.

6 Decarbonising industry - specific technologies

The industry sector has several unique processes that represent major sources of emissions and cannot be analysed from a general view. Below follows our chapter describing some of the opportunities and challenges that exist for the major industrial processes in Sweden, e.g. steel, cement, paper and pulp, aluminium, petrochemicals and fertilisers.

6.1 Steel: new reduction agents

About two thirds of the steel production in Sweden is ore based[10], primary steel production, in which iron ore is first reduced to iron in order to make steel. The reduction of iron ore into iron accounts for about 80% of the carbon dioxide emissions from primary steel production. Apart from increasing the percentage of scrap-based production, finding new reduction agents is, therefore, the most important step towards decarbonising the steel industry. Three alternatives exist; to use hydrogen as a reduction agent, to reduce iron ore in electrolysis or to use biochar instead of coke. Hydrogen reduction and electrolysis has the advantage over biochar that the primary energy can come from any renewable resource which may prove to be important in a low-carbon future where biomass is wanted for production of both energy and materials. In direct reduction (DRI), natural gas could also be replaced by biomethane. The biomass options do not differ technically from existing systems which is why only electrolysis and hydrogen as reduction agents are explained in more detail below.

Hydrogen as a reduction agent can be used in existing direct reduction shafts but new furnace designs may be beneficial if hydrogen is to be used on a large scale to avoid unwanted side-effects such as sticking (Sohn, 2008). New reduction techniques, such as suspension reduction, being developed at the University of Utah, also have the advantage that the iron ore does not have to be sintered or pelleted which will reduce the energy use in steel making compared to current technology (Sohn, 2008). The reduction process is much faster with hydrogen than with coke but is endothermic as opposed to the latter, which is why heat must be added (Choi, 2010; Ranzani da Costa, 2009). The extra heat can be supplied by burning excess hydrogen or using electricity (e.g. microwave technology), the latter option being more energy efficient. Only about 60% of the hydrogen can be utilised in the process, so the gas must be recirculated. The amount needed depends largely on the temperature and required speed of the reduction, which is why lower amounts of excess hydrogen will be needed in a mature technology. The flue gas from reduction with hydrogen will be mainly water vapour which could be used for new hydrogen production to increase the energy efficiency in water electrolysis. About 3.45-3.95 MWh of electricity would be needed to produce hydrogen for reduction of 1 tonne of steel using an electrolyser with 80-70% efficiency LHV. Electrolysis of iron ore to produce iron is also possible. This process is known as electrowinning. The iron ore can be solved or suspended in an acid or alkaline solution to enable the process. It can also be melted in a saline solution for high temperature electrolysis (above 1600 °C). If the iron is not melted the electrolysis, it can be performed at 110 °C. The studies show that 2.8-3.2 MWh/ton sponge iron is needed for the

[10] 1/3 is based on melting scrap iron in electric arc furnaces. This requires high use of electricity but reduces CO_2 emissions substantially as there is no need to reducing iron ore with coke or pelletisation.

electrowinning process (Cox and Fray, 2008; Allanore et. al., 2010). With electricity for melting included this would be approximately 3,7 MWh/ton steel.

To reach near zero carbon emissions, however, measures of reduction must be carried out also in other processes at the steel plant. If electrowinning in an acid or alkaline solution or hydrogen reduction is used, the iron ore is reduced in solid state, creating sponge iron which must be melted afterwards for alloying purposes. EPRI (2009) suggests using advanced plasma or induction ovens for smelting. The key benefits besides lower emissions will be higher thermal efficiency and fewer waste products. Gasified biomass could be used for substitution of oil and propane in heat and heat treating furnaces; with a new technologies for gasification that reduce the tar content of the gas while creating a gas with higher heating value, compared to similar technologies (Ponzio, 2008).

New reduction methods offer some advantages to current production apart from lowering emissions of carbon dioxide. Coke contains sulphur which must be removed from the steel. Approximately 100 Nm^3 of oxygen is needed in order to reduce the concentration of carbon in steel production today. As requirements on low sulphur and carbon content in some speciality steels grow, using reduction methods free from carbon may reduce costs. To make a breakthrough in the use of new reduction methods in steel industry this must be recognised as a long-term strategy since the plant life times are long and infrastructure investments large. The use of hydrogen as a reduction agent could also be utilised as a means of energy storage and load smoothing in the electricity grid. This possibility must be investigated further.

6.2. Cement: alternative heat and new materials

Emissions of greenhouse gases in cement production are caused by two factors; burning of fossil fuels for heat (40%) and in the calcination of limestone to chemically reactive calcium oxide (60%). By deploying a new oxy-fired process with CCS, cement production can in the long-term reach near-zero emissions. If the oxy-fuelled process is fuelled with a substantial share of sustainably grown biomass the emission can potentially even be carbon negative.

The cement industry uses between 3 to 4 GJ heat /ton of clinker produced (Åhman 2004). The heat is supplied at the temperature of 1500 °C degrees in the rotating kiln. This high temperature has made the cement industry a good candidate for burning waste materials with high heating value such as used tyres. The cement industry in Europe/Sweden supplies approximately 30% of its input energy for heat from alternative sources. However much of the alternative energy used, in form of heat, is still of fossil origin (e.g. used tyres). It is technically possible to replace this energy with sustainably produced biomass in the long-term, however there will be a need for pre-treatment of the biofuel to ensure the high combustion temperature needed in the process. Torrefaction of biomass (wood and waste) to produce “green coal” as a suitable replacement for fossil coal is being studied in the cement sector. Globally 8% of fuels used for calcination is biomass (ECRA 2009), mostly sewage sludge, meat and bone meal, waste wood, and sawdust.

An alternative to build cement on calcium carbonates and thus avoid the process emission from the calcination process is to use another basic material. Readily available materials for cement production are $CaCO_3$, SiO_2, Fe_2O_3 and Al_2O_3 (Schneider et al. 2011). A number of suggested alternative materials that can replace Portland cement have been suggested, with more or less promises of reducing carbon dioxide emissions. See Juenger et al. (2011) and Gartner and Macphee (2011) for an overview.

Magnesium-based cements are one prominent alternative. The idea is not new but many of the alternatives are too water sensitive for outdoor use and suffer from high cost why a widespread use is not possible. Novacem in the UK has developed magnesium-based cement that can utilise captured CO_2 and thus have the potential to become a carbon negative building material if carbon free energy is used during manufacturing. The Novacem cement is a mix of magnesium oxide (MgO) and hydrated magnesium carbonate ($xMgCO_3 \cdot yMg\ (OH)_2 \cdot zH_2O$). The main benefit for the Novacem cement compared to other magnesium-based cements is that the MgO can be extracted from common magnesium silicate rocks, which are very abundant (Gartner and Macphee 2011). It is the magnesium carbonate that absorbs carbon dioxide when it is produced in the reactor (Fagerlund, 2011). Magnesium silicates is heated to a temperature of 170 °C, reacts with carbon dioxide, water, and some additives to form MgCO3. The magnesium carbonate is heated to 700 °C to form MgO, releasing CO_2. This CO_2 is recycled to the first part of the process, and reacted with the hydrated magnesium carbonate. This latter product is mixed with the MgO to form cement (Gartner and Macphee 2011).

In California the company Calera is using CO_2-rich flue gases that react with Ca (or Mg) in waste water streams, ponds or seawater to form vaterite, imitating the formation of coral reefs. Vaterite is an unstable form of CaCO3 which stabilise into calcite or aragonite in contact with water (the stable state depends on the temperature conditions) (Pattersson, June 2011). Crushed and dry vaterite can be used as cement. Depending on the carbon dioxide source and the energy used in the process, the Calera cement can be carbon negative. Little public data on the technology is available why a more thorough assessment is not possible.

A third alternative is to produce cement completely from industrial waste. Cenin in Great Britain has reduced the emissions emanating from production with 95% compared to standard Portland cement. The industrial waste is thermally treated to be made reactive. Energy is saved since the material does not have to be quarried. If the energy used in the manufacturing process were substituted by renewable energy sources the resulting cement could be near-carbon neutral. Production started in 2008 and products are tested following European standards (cenin.co.uk, March 2012). The company CeraTech in the US is also producing cement from waste materials and other scientific studies have confirmed that industrial waste can successfully be used as cement (Yen et al. 2011).

The introduction of a novel cement type is no easy task. The cement manufacturing industry is tightly linked to the users in the building industry and the market strongly depends on trust and several decades of development of standards and building codes adapted to the specific needs and technical features of standard Portland cement. A new type of cement needs careful and long-term testing before it could be applicable in the building sector at any large rates since, for example, hardening properties could be different and are most crucial (Fagerlund 2011). Another crucial factor for successful implementation on a large scale is the corrosion protection of steel in reinforced concrete, which constitutes the major part of concrete for construction purposes. Ordinary Portland-cement is highly alkaline, while new cementitious materials are less so, which may make them less suitable for long-lasting constructions such as buildings or bridges since the durability of reinforced concrete largely depends on the corrosion of steel rather than the concrete itself (Gartner and Macphee 2011). Alternative cements will most likely have to start in niche applications to prove economic viability and to gain experiences on the long term durability and strength.

6.3 Chemical paper and pulp : blackliquor gasification and CCS

Chemical pulp mills are today the major users of biomass for energy in Sweden and represents 70 % of total pulp production in Sweden[11]. With a large total energy demand but relatively small GHG emissions due to the large share of biomass use, an important role of the paper and pulp industry in a future carbon constrained world will be that of a supplier of renewable fuels and/or electricity and carbon negative emissions.

Current chemical paper and pulp mills still use some fossil fuels, mainly oil, for heating purposes in the lime kiln, and import electricity from the grid. However, modern and new mill designs with substantially increased energy efficiency and less heat demand will allow for pulp mills to become self-sufficient in energy. The inflow of the embodied energy in the biomass to the pulp mill will be sufficient for producing the pulp and also for exporting heat (KAM 2003). For an integrated paper and pulp mill that uses more steam, even with currently best available technology there will still be a small need for importing energy (FRAM 2005, Pettersson 2011).

A future potential for the paper and pulp mills is to develop and introduce black liquor gasification (BLG). The black liquor, a process intermediate that consist of lignin, hemicelluloses and cooking chemicals, is today used internally in a recovery boiler (RB) to produce heat (steam) and for regenerating the cooking chemicals. The idea with gasifiying the black liquor, instead of combusting it in a recovery boiler is to increase the quality of the embodied energy in the black liquor. This will enable a wider use and value of the energy for either electricity production or as transport fuels or even as basic chemicals. Black liquor gasification will however result in a steam deficit even for modern mills based on BAT. This energy must be compensated by combusting imported low grade biomass such as bark fellings (Pettersson 2011).

The black liquor gasification process result in a syngas (HC and CO) that, after cleaning, can be further processed to hydrogen, methanol of Fisher-Tropsch diesel, or for combustion in a CHP. Combining black liquor gasification with increased energy efficiency can thus result in a pulp mill producing pulp and electricity and/or motor fuels with that embodied in the inflowing biomass[12]. Another key advantage with black liquor gasification is that you separate the CO_2 in the process, thus making the incremental cost of applying CCS substantially lower compared to the incremental cost for applying CCS at the recovery boiler.

Black liquor gasification has been studied for several years and several different gasification technologies have been proposed. Today, two main systems remain in development, entrained pressurised oxygen blown gasification and fluidised bed gasification (Modig 2005). Pressurised

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[11] The remaining 30% of production is mechanical pulping. We do not address mechanical pulping further in this paper.

[12] However, the amount of input biomass will increase as the out-put energy also increases (power/motor fuels)

oxygen blown gasification is developed by Chemrec in Sweden and has been tested in Piteå. The financial and technical risks of developing commercial black liquor gasification should not be underestimated, see e.g. (Modig 2005). For gasification in general, there is still some technical problems with cleaning the syngas from tars that will foul the up-stream processes or turbine. Syngas cleaning is under development and is demonstrated in several configurations. However, it remains to be proven whether it is reliable in large-scale configurations. There is also for black liquor gasification the problem with introducing a new concept that requires substantial up front funding and has so far a relatively uncertain market (e.g. the market for alternative fuels such as DME or the price of electricity). However, a pilot scale production plant with a combined motor fuel production for approximately 2000 trucks is under construction in Piteå.

Other future routes for increasing the out-put of usable products from the inflowing biomass in a paper and pulp mill is to keep the recovery boiler and extract lignin for producing base chemicals (Pettersson and Harvey 2012) and extracting cellulose for producing ethanol (Fornell et al 2010). However, producing DME/Methanol from BLG is in most future scenarios regarded as the most profitable (see e.g. Pettersson and Harvey 2012)

6.4. Petrochemicals and refineries: replacing petroleum with biomass

Refineries and the production of petrochemicals are built around using petroleum as feedstock for producing fuels and chemicals resulting both in direct process related emissions and down-stream emission at the end-of-life for the products (plastics and transport fuels). In a carbon-constrained world, these down-stream emissions will also be regulated and this could have large repercussion for the petrochemical sector.

The emissions originating from the part of the feedstock that is combusted for producing heat and electricity for processing needs can be reduced, at least partly, with CCS focusing on the major exhaust stacks. The cost of applying CCS will increase substantially and require major refurbishment if all emissions sources within the refinery/chemical sites are to be captured (DNV 2011).

However, the major part of the carbon (80 - 90%) is locked in the products produced (petrol/diesel/chemicals). The emissions originating from this carbon will be accounted for either at the combustion source in e.g. transport or power sector or end up in the waste emission statistics (e.g. a majority of plastics). For refineries, the embedded emissions are the major impacts on climate change. This is a major reason as to why the number of refineries will decrease substantially in a carbon constrained world as the demand for the products (fossil based fuels) will diminish. The Swedish refinery sector has managed a declining domestic demand by increasing the exports of fossil fuels with high environmental quality (low sulphur fuels). The export market today constitutes a major share of Swedish refinery market (>60%).

The refinery sector is tightly linked to the petrochemical sector that uses products[13] (mainly naphtha) from refineries as feedstock and converts this to a range of petrochemicals. With the long-term climate policy induced decrease in demand for fossil fuels, the supply market for

[13] Approximately 5% of the incoming petroleum feedstock goes to the petrochemical industry

naphtha will change, as the whole refinery industry will need to restructure substantially. With potentially no domestic demand for fossil fuels by 2050, the remaining fossil-based refineries will have targeted a most likely very limited export market in developing countries.

A main option from a climate change perspective to face these challenges is a transition from petroleum based chemicals to biomass based chemicals[14]. This transition has already started in the transport sector with the 1st and 2nd generation of biofuels. Also in the chemical sector increasing shares of bio-based chemicals have been seen the last 10 years. In the long-term, this can enable new bio refineries that, like paper and pulp mills would only need to use the embodied energy in the incoming biomass to produce fuels and platform chemicals. The are several proposed routes for producing a number of suitable chemical feedstock from biomass including the currently deployed feedstock stemming from ethanol production or extraction of fatty acid esters from vegetable oil. However, the largest biomass resource is lignocellulosic biomass stemming from wood (including energy crops), agricultural waste and household waste. In order to replace the huge volume of petrochemicals, focus in the future will need to be on utilising woody biomass as feedstock instead of sugar and starch based biomass. This is due to higher output per hectare, less input energy needed and less potential conflicts with alternative uses (e.g. food) (van Haveren et al 2007, Ren et al 2009).

Several routes exist that technically could transform various types of biomass to useful chemicals. One strategy is to use the naturally complex structure of the biomass and process it to usable platform chemicals. A good example is the current use of starch based chemicals in special cases (Brehmer et al 2008). The other routes are to separate, with varying degrees, the biomass into either fermentable sugar via hydrolysis (the biochemical route) or into syngas via gasification (the thermo-chemical route).

The main thermochemical conversion route is to gasify everything into syngas and from there to methanol or ethanol, see e.g. Larson et al (2010). Other thermochemical routes that can contribute to specific chemicals are pyrolysis, flash pyrolysis or hydrothermal upgrading (HTU). These methods result in varying types of "biocrude" that resemble naphtha and can be converted into ethylene etc. with minimal development in the synthesis step.

With gasification, the biomass is split into CO and HC (syngas) that later can be rebuilt (synthesised) to (at least theoretically) any kind of polymer or fuel you want. Gasification transforms all the biomass including the lignin. Gasification is a strategic technology that eventually is beginning to emerge on the market. So far mostly as large pilot plants such as the now decided Gobigas project in Gothenburg (Gobigas 2012). Gasification of biomass produces tars (contrary to gasification of coal) and cleaning of the biobased syngas is still an issue that needs further development to become commercial. Gasification uses mainly pre-prepared woody biomass but development will make possible for practically any carbonaceous feedstock to be used including waste. The main barriers for commercialisation today are to gain experiences and knowledge in building and integrating large-scale gasification systems. The market is still

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[14] A transition away from oil is also explored in China. However, here the Chinese also look at gasifying coal and use this as a feedstock for both fuels and chemicals. This will substantially increase emission compared to fossil fuels and chemicals.

uncertain for private investors and there are some technical issues with cost-effective gas cleaning, etc, that will have to be resolved with further development (Åhman 2009).

For the biochemical route, the three parts (hemicelloluse, cellulose, and lignin) needs first to be separated. Then the hemicelluloses and the cellulose can hydrolysed into sugars that can be fermented to ethanol. Lignin could either be depolymerised or further processed to aromatics or used as energy (both heat and electricity possible). Converting cellulose is the most difficult part today that is in need for further development of cellulases for enzymatic hydrolysis (hemicelluloses can be effectively hydrolysed using "standard" acid hydrolysis. Depolymerising lignin does also require scientific development before competitive.

Replacing all relevant chemicals with lignocellulosic biomass feedstock is estimated to require 18 to 40 EJ of biomass every year (Cherubini and Strömman 2011). Currently the use of biomass for energy purposes is 50 to 55 EJ/year[15] and the future potential of modern bioenergy supply varies greatly between 170 to 250 EJ/year (Börjesson et al 2008). Replacing the currently produced 620 000 ton of ethylene and 200 000 tons of propylene in Sweden would require 3 to 3,5 Mtonnes of woody biomass components (based on Cherubini and Strömman 2011, note that this would also result in 1 Mton lignin). Biomass-based chemicals are currently growing but most in segment where the specific biomass has advantages over petrochemicals based routes or where there is a strong consumer demand for bioplastics. However the increasing volatility and insecurity of the basic petroleum feedstock has increased interest substantially the last years for also producing basic platform chemicals such as olefins and aromatics from biomass. In Sweden, the petrochemical cluster in Stenugnsund has embarked on an ambitious vision to become sustainable by 2030 relying only on biomass based feedstock (www.kemiindustrinistenugnsund.se 2012).

6.5 Primary aluminium: inert anodes

The production of primary aluminium has from the beginning relied on the Hall-Heroult process using electrolysis for separating pure aluminium from alumina (aluminium-oxide). Primary aluminium production is thus a very electricity intensive industry. Assuming carbon free electricity and carbon free upstream mining practices (mainly heat and transport fuels for separating alumina from bauxite) the remaining emission to be mitigated are from inefficient process resulting in the emission of PFCs (the anode effect) and the depletion of carbon at the anodes when melting the alumina. The "anode effect" and the associated emission of PFCs can be further optimised and have already decreased by 80% in the OECD area the last 15 years on a voluntary basis. However, when smelting the bauxite, the carbon cathodes are eventually depleted resulting in CO_2 emissions of approximately 1, 4-tonCO_2/ton aluminium produced. Research for developing inert anodes that do not deplete when used has been on-going for several decades. Inert anodes will not only diminish both the PFCs and the CO_2 emissions but also reduced the energy demand substantially. Thus this research is also motivated for pure economic reasons for companies. Currently, several inert anodes are being demonstrated and tested for viability and are hoped to enter the market within 10 to 15 years, see e.g. IEA 2011.

[15] However, the majority of this (40 to 45 EJ) is traditional (e.g. not traded) biomass in developing countries

Aluminium has the advantage of being possible to recyclable indefinitely and the energy use and emission are substantially lower for secondary aluminium compared to primary aluminium.

6.6 Fertilisers (nitric acid): improved catalyst

The production of fertilisers is a major source of emissions globally but this production has decreased substantially in Sweden the last years. The nitric acid used for fertilisers in Sweden is imported and the only production of nitric acid in Sweden is used for industrial explosive (Yara 2012).

However, when producing nitric acid, the process emits N_2O in the flue gas and of course CO_2 emission on the process requiring heat and electricity. The emissions of N_2O are today reduced substantially in Sweden. The introduction of catalytic converters have reduced emission with >90% the last 10 years. No other alternative technology is currently being investigated as catalysts are assumed to will probably be improved even further in the future.

7 Options for decarbonising – a technical summary

It appears *technically* possible to develop technologies to decarbonise industry completely and even to achieve negative emissions. A continued strong focus on energy efficiency and the wider introduction of bioenergy and CCS is both anticipated and necessary. However, for a complete decarbonisation, most zero-emission solutions for the industry depend on novel process designs that so far only exist in research laboratories or in small-scale demonstration projects. Below we summarise the development necessary for decarbonising the basic material production in Sweden.

7.1 The production of steel

For decarbonising the steel sector, substantial changes to the processes of steel making need to be implemented. Continued efficiency is important but most steel mills today operate close to theoretical limits in their existing core processes (Birat 2010).

For a complete decarbonisation that would make iron-ore based steel production inherently carbon free the introduction of electrowinning or hydrogen as a reduction agent is necessary. These methods are yet only being researched at lab-scale and need substantial and long-term support for moving towards demonstration scale. First then is it possible to assess fully the future potential for market competitiveness. Both hydrogen and electrowinning would substitute coke/or biochar with carbon free electricity and thus increase the demand for carbon free electricity. As an example, replacing the current iron ore based production of steel in Sweden with electrowinning would roughly replace the currently used 17 TWh coke[16] with a similar amount of electricity (numbers are rough as the technology is only on a lab scale) and reduce emissions with 7 MtonCO_2/year. Electrowinning would decarbonise the steel sector without the need (and possibility) for CCS. Roughly the same figures would be valid for hydrogen as a reduction agent. It is noteworthy that a typical integrated steelwork would become the largest single power consumer if hydrogen or electrowinning were introduced. Other options for decarbonising steel production include the extensive use of CCS coupled with the replacement of fossil-coke with bio-coke.

The introduction of CCS for steel production is complicated and requires substantial redesign of several key processes. CCS with TGR-BF is the main option to retrofit capture technologies to existing blast furnaces. However, this alternative still requires technical development and will only capture between 35 to 75% of the total CO_2 emissions depending on whether other major emission sources within the mill (e.g. sintering) are included (UNIDO 2011).

The major emission source (the reduction of iron ore with coke) can theoretically be mitigated by replacing fossil coke with bio coke (pre-treated biomass) in blast furnaces. For direct reducing iron (DRI) production it is technically possible to replace natural gas with biomethane**.** A

[16] Roughly 10 to 12 TWh would be needed for the reduction and the rest for other needs that now uses the spare heat from the coke

combination with the use pre-treated biomass ("biocoke")[17] as a reduction agent and carbon capture on the major flows of CO_2 could probably make steel production CO_2 –neutral.

7.2 The production of cement

For a complete and inherent decarbonisation of cement manufacturing it is theoretically possible to develop and replace current clinker with other material. The options of changing the basic materials used for avoiding "process emissions" in cement manufacturing is being developed and look promising (e.g. magnesium based cement or cement made form sewage sludge). Hopefully these alternatives will soon find a suitable market niche from where they can grow and the technical properties and economic costs will become more known. However, the long-term challenges of substituting Portland cement as the basic building material should not be underestimated. And even if we assume that "classic" cement will still be the main material for construction in 2050 there are still technical solutions at hand.

CCS and the introduction of pre-treated biomass can reduce emission substantially. However, for capturing all CO_2 emissions, the cement production needs to introduce oxy-fuel processing. This could potentially capture all CO_2 created in the process of cement manufacturing including the process-related emission. Oxy-fuel processing first needs to be tested and demonstrated for proving technical performance on the clinker and the economics.

Another option is to rely on post-process capture with relatively well-known technologies (chemical absorption). This will not capture all emission but together with the increased use of pre-treated biomass for combustion the facility as such could become carbon neutral. The full capture of all CO_2 emissions with oxy-fuel could result in negative emissions if the heating in the cement kiln is partly or fully based on pre-treated biomass (approximately 40% of total emissions form a cement plants comes from heating).

As an example, if we assume 2,4 Mton of CO_2 emissions from future cement factories in Sweden (based on IVL 2050 scenario), then approximately 1,6 Mton of these CO_2 emissions could be of biological origin and thus result in negative emissions if captured and stored. The use of CCS will increase the demand for low-grade heat for capturing. This includes the production of oxygen, compression, etc. Capture 2,4 MtonCO_2 in a oxy-fuel process will roughly demand 0,07 TWh of extra heat and 0,25- 0,30 TWh of extra electricity (calculation based on numbers from Mott McDonald 2011).

7.3 The production of paper and pulp

Few analysts doubt the ability of the paper and pulp sector in Sweden to become carbon neutral. The remaining and limited fossil energy use in the paper and pulp sector is technically possible to replace in the given time frame. The paper could play that a major role and pulp sector in a climate restricted world would be to also become a supplier for renewable energy and chemicals in biorefineries and, together with CCS, a future source of negative emissions.

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[17] The use of biocoke in smaller steel mills exist in Brazil

An interesting future route for the pulp and paper industry is to gasify the black liquor and produce syngas from which several fuels/chemicals or electricity can be produced. Increased energy efficiency as a result of new brownfield investments is a key strategic priority for enabling the pulp industry to transition towards “biorefinery concepts”. Reducing the steam demand for the pulping process and for the paper production will enable the industry to transform a greater share of the incoming energy embodied in the biomass into electricity, fuels and chemicals.

The second major effort for reducing emissions in the scenario is the application of CCS to the major flows of biogenic CO_2 stemming from the chemical paper and pulp mills. The paper and pulp sector in Sweden currently emits approximately 22 Mton of CO_2 from biological origin[18] (VTT 2010). This is approximately equal to the amount of fossil CO_2 emitted in the whole Swedish industrial sector. With CCS from the major recovery boilers would be technically possible to capture a major share of these biogenic CO_2 emissions.

If electricity or hydrogen is produced then potentially all biogenic CO_2 could be captured. The potential to carbon negative emissions will decrease if a carbon based fuels are produced and exported, e.g. methanol. With methanol, approximately 50% of the CO_2 will leave the factory embedded in the fuel and not available for CCS. Retrofitting CCS to current recovery boilers without increased efficiency is doable but less economically attractive (ECN 2011).

If all the biogenic emissions from the current volume of chemical paper and pulp mills would be captured this would result in approximately 15 MtonCO_2/year of negative emissions. Capturing 15 Mton CO_2/year from recovery boilers with chemical absorption would increase heat demand with 12 -13 TWh of heat and 2- 2,2 TWh of electricity for compression.

7.4 The production of fuels and chemicals

Future fuel factories in Sweden could be based on biorefinery concepts replacing current petrol and diesel production in existing petroleum refineries. A biorefinery can not only become carbon neutral (relying solely on the incoming energy in the biomass) but could potentially also become future sources for negative emission if the process-generated biogenic CO_2 emissions are captured. Biogenic emissions from future biorefineries producing transport fuels will be an opportunity to capture biogenic CO_2 emissions with low economic and energy costs as part of the inflowing carbon is separated as CO_2 during the process (Lindfeldt and Westermark 2009).

Future fuel factories could be a source of both carbon neutral fuels and negative emissions. The amount depends both on how much biofuel will eventually be produced in Sweden and the choice of feedstock (agricultural or wood). For future gasification, the potential is relatively clear and advantageous but there exist also an opportunity for capturing biogenic CO_2 from process heating in wheat based ethanol production (Carbo 2011). As an example, if Sweden would produce 50 TWh[19] of methanol/DME via gasification this could give a possibility to capture roughly 9 Mton of biogenic CO_2 emissions[20].

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[18] The total emission of biogenic CO_2 is 29 Mton according to VTT 2010 including e.g. CHP in district heating and power production

[19] Current energy use in the transport sector is 90 TWh but the potential for energy efficiency is great.

The production of basic chemicals (ethene and propylene) in Sweden is primarily based on ethane derived from refineries close by. In order for the petrochemical industry to become carbon neutral and avoid both direct emissions at the plants and down-stream emission from the combustion of degradation of the plastics products at the end of their life time the petrochemicals industry will need to shift to biobased feedstock. The future market for refineries will change substantially the coming 20 to 30 years in climate restricted world. This transition has already begun in small scale and which direction more exactly it will take in the future is difficult to predict. For the major flows, most analysts see a large role for both gasification and various types of biochemical conversion routes in future biorefineries for producing biobased bulk chemicals.

With a transition towards biobased petrochemicals, the demand for biomass will increase. As an example, replacing the current production of ethene and propylene in Sweden would need an extra of 3-4 Mton dry wood/year, representing roughly 15 TWh/year.

[20] Calculation roughly based on Lindfeldt and Westermark (2009) and their "high efficiency" case.

8 The context for climate policies and technical change

Decarbonising the industrial sector while maintaining production volumes requires a major effort to develop, introduce and replace existing technologies with advanced lean-carbon technologies. Relying on current technical production systems and applying “end-of-pipe” solutions can reduce emissions substantially but will be insufficient for reaching zero emissions. In most cases it is thus necessary to introduce completely novel core process designs for attaining zero emissions.

Most industrial facilities in Sweden and the EU have been commissioned before 1980 (Rootzén 2012) and it is likely that most of them will be completely rehauled or replaced in the time frame up to 2050. An effective long-term policy targeting zero emission must aim for making the industrial sector “zero emissions technology ready” in this time frame. Being “zero-emission techniology ready” means having the technical know-how, the experience and the financial ability to invest in future zero emission process technologies. This requires thus a substantial amount of research, development and large scale demonstration and deployment efforts for proving technical and economic feasibility. Zero emission technology systems need to be both technically and economically within reach for the industry at the time when the next major investment decisions will be made.

Governments have a key role in setting the playing field to enable industries to act in the interest of global environment and invest sufficiently in a transformation towards zero emissions. However, the role that national climate policy can play is influenced strongly by the global policy frameworks for both climate and e.g. trade regulations, by the climate policy frameworks adopted on an EU level and also by competing domestic policy objectives (regional growth, fairness, distribution, other environmental objectives, etc.). An optimal policy mix for supporting technical development and cost-efficient mitigation needs to consider all limitations in choice of policy instrument that comes from global burden sharing principles, free trade, public acceptance etc.

Below in chapter 8.1 we first outline the current dominating policy frameworks influencing long term industrial mitigation (the EU ETS and the UNFCCC). We assume that the EU ETS and the basic principles of the UNFCCC will continue to set the framework for Swedish climate policy in the long-term. In the following chapter 8.2 we briefly review some of the theoretical ideas on technical change and public policy that is appropriate and applicable to our perspective in this report.

8.1 The EU ETS, burden sharing principles and carbon leakage

The primary climate policy instrument affecting the industry in Sweden today is the EU ETS that puts a cap on emissions for the EU industry and power sectors. The cap results in a price for the emission allowances. Since the introduction in 2005, the prices for emissions rights rose to up to 30 EUR/tonCO_2 at it’s highest (just before the financial crisis) but have since then hovered around 6 to 10 EUR/tonCO_2. As a contrast, the long-term projections for emissions in Sweden assume, in line with the EU commission calculations, that the prices within the EU ETS will average around

16 EUR/ton CO_2 up to 2020. A low price in a cap-and trade system is not a problem if the cap is set properly according to set long-term political ambitions (2-degree target implying -85% by 2050). However, the current cap within the EU ETS system is only regulated until 2025 and with an ambition (-1,74%/year) that is not consistent with the long-term EU target of -85% by 2050. The price in the EU ETS does thus not currently reflect the costs of a long-term decarbonisation strategy[21]. This is a major problem since a cap-and-trade system does not only put a cap but also a floor on future emissions. Furthermore, a low carbon price that does not correctly reflect the long-term ambitions will not lead to level of increased strategic development (e.g. research and innovation) either.

8.1.1 Pricing carbon and leakage

Priced based system (taxes or trading schemes) could work well for guiding emission reductions in mainly domestic sectors such as the EU power sector or the road transport sector[22]. Industry is, contrary to the power sector, often (not always) competing on a global market with industries from countries that are not subject to any climate polices. Thus, for industries with a high share of trade and a CO_2-intense production, there is an obvious risk of carbon leakage. The risk of carbon leakage limits the effectiveness and acceptability for forcing future emission reduction with a tighter cap/higher price. However, the risk for carbon leakage is also inherent in the basic burden sharing principle of the original global framework convention for climate change (UNFCCC). Several proposals have been put forward for dealing with carbon leakage.

Japan proposed to separate the CO_2-intensive industrial sectors from future country-based commitments and treating industrial sector separately with common global commitments in a “sectoral approach”. This proposal was forcefully rejected by developing countries in the negotiations on the basis that it broke with the key principle of “common but differentiated responsibilities” in the convention.

Several academics have suggested using various versions of border tax adjustments[23] for energy intensive products entering the EU from countries without any binding climate commitments, see e.g. Frankel (2008). This possibility was also included in the earlier US climate policy proposals (e.g the Waxman-Markey bill) and has also been proposed in the EU by France. Border tax adjustments are not currently pursued by any party in the convention, largely due to the risk of infringing on free trade policies and also for breaking the burden sharing principle. However, the unilateral decision by the EU to mandate all international air carriers landing in the EU to buy emission rights or to demonstrate that they are subject to similar climate policies domestically can be viewed as a light version of the carbon border tax adjustment idea. This unilateral decision has so far been strongly rejected by e.g. China and also the US and challenged in court and it is still unclear whether it will be accepted internationally.

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[21] Several other effects such as the unexpected down turn in 2008-2009 that created a “surplus bubble” in the system, the possible restructuring of some major emitters, etc. and a general uncertainty regarding the future of the global climate regime and how that will affect the EU climate regulation has also put a downward pressure on the EU ETS allowances.

[22] However, even so, governments within the EU have introduced several specific policies for reaching specific renewable energy targets (e.g. the green certificate scheme in Sweden)

[23] Sometimes also called Border Carbon Adjustments

Instead, the currently used method by the EU for minimising carbon leakage is to allocate the initial emission rights for free. With free allocation the company only suffers from an extra emission cost on the margin[24] and the free allocation can be regarded as a subsidy for maintaining production levels. Free allocation was the general principle in the two first phases of the EU ETS (from 2005 to 2012). So far, econometric studies suggest that the strategy of free allocation has worked in avoiding measurable carbon leakage from EU industry (Reinaud 2008, Grubb and Neuhoff 2006). However, as also noted by several academics, during the two first periods of the EU ETS, economic growth was very strong in the EU area potentially masking some of the carbon leakage.

In the third period, the allocation of free emission rights will still be used in the EU for industries at risk of carbon leakage. However, the allocation will be less compared to the 2 first trading periods and will roughly correspond to 90% of overall industrial emissions according to predefined benchmarks. Also, the emission cap within the trading system is further tightened and the price is expected to increase in the long term. In the long term, it is reasonable to expect that the real risk of carbon leakage will increase despite free allocation. Future carbon leakage is likely to foremost manifest itself as a discouragement of new investments within the EU. Here, it will be difficult to separate the effects of the EU ETS and the effects of normal market dynamics with increasing share of investments seeking opportunities closer to emerging markets.

The burden sharing principle in the UNFCCC does not mean that transitional countries could continue without restrictions on CO_2-emission indefinitely (the current Kyoto-framing). The intention in the UNFCCC is that transitional countries should eventually accept future restrictions on CO_2 emissions. The timing and size of these restrictions are contested. Decarbonising the last 20 to 40% of CO_2-emisison in society beyond 2030 will come at a high marginal cost (such as the industrial process emissions covered in this report but also parts of the transport sector and aviation). Without phasing in CO_2 -restrictions resulting in similar “carbon costs” in transitional countries, domestic compensation or border carbon adjustments will become necessary for maintaining basic materials production within the EU in the long-term.

The future risk of carbon leakage should also be seen in the light of current existing trade restrictions and slow progress on free trade negotiations where several countries in practice maintains the right to discourage foreign market access and protect domestic industries following national policy goals. Widening the focus, possible policy responses to the threat of carbon leakage could thus also include increased emphasis on fair trade, less market distorting industrial policies, fewer subsidies for inputs like electricity and coal/natural gas and greater access to markets. This is especially valid for the fast growing economies that no longer are in need of international support for poverty eradication (China, Brazil, India, South Africa, Vietnam, etc.) but where focus has shifted towards bilateral co-operation. The question of carbon leakage points to the fact that global climate policy is today more and more interlinked with general global policy issues as a response of globalisation.

[24] Economic theory would suggest that free allocation should not influence marginal production decisions in industry assuming that business take full account for the alternative income of selling the excess emission rights. However, industry practice as observed in general deviates from this “theoretical” behavior (Carbon Trust 2008)

The risk of carbon leakage highlights the difficulties of relying too much on the carbon price as a driving force for emission reduction in a world where we need to accept different carbon prices as a consequence of the burden sharing principle.

In the long-term, global trade policy and climate policy are likely to merge. The use, or threat of using, trade policy measures such as border carbon adjustments have been suggested as a tool for implementing a global treaty (see e.g. Barret 2011, Helm et al 2012).

8.2 Policies for reducing emissions and supporting technical change

The safest long-term policy response to minimise both global emissions, carbon leakage and at the same time enhance EU industrial competitiveness is to enable the development and introduction of competitive carbon lean technologies.

To put a price on the emissions of greenhouse gases and internalise the *negative externalities* is generally put forward as the major policy instrument for achieving emission reductions cost efficiently. The principal rationale is that a price will provide the actors with the highest degree of flexibility for achieving a target and thus enabling societal cost efficient mitigation. A second often highlighted rationale is also that a price on emissions will induce more long-term private investments into research and development for new carbon lean technologies. Most economists generally also concludes that relying only on a price on the emissions for driving long-term systemic technical change is insufficient for achieving cost-effective mitigation (Fisher and Newell 2008, Popp 2010, Hanemann 2010, IPCC SREEN 2011) as technology development yields many positive externalities.

However, how broadly one should interpret the term "technical development" and exactly how and, not the least, how *technology specific* and how much market creating support should be given is debated among academics (see e.g. Azar and Sanden 2011; Fisher et al 2012).

From a mitigation perspective, what is important is not the inventions or innovations as such but the broad *use* of novel carbon lean technologies. Thus, we thus use the term "technical change" for analysing the process from the first ideas all the way to the technology becoming the dominating design on the market.

8.2.1 Supporting long-term technical change

The research field of innovation and technical change is large and covers several different academic perspectives[25]. However, common features of these studies in what influences and drives technical change is the embeddedness of technology into a wider institutional and economic context and that technical change is inherently uncertain, cumulative and will create new and unanticipated solutions by combinations.

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[25] See e.g. studies on Innovation systems (Lundvall 1992, Rosenberg 1982, Jacobsson and Begek 2004), on sociology (Bijker 1995; Callon 1980), on technical regimes and niche market management (Dosi 1982, Kemp 1997), and policy studies (Norberg-Bohm 1999, Wallace 1995) for mentioning just a few.

The institutional context includes legal frameworks, standards, education systems, research funding agencies, consumer and engineering habits, and networks of both public and private actors. The economic context includes economies of scale, sunk cost, and increasing returns of adoption from decades of learning for incumbent technologies. Thus, both the institutional and economic context strongly influences the speed and direction of technical changes in society and also effectively acts like barriers for new alternative technologies.

Technical change can also be analysed from a multi-level perspective, which is one of the newest academic perspectives on innovation and technical change. The "multi levels" refers to the three different levels in society; niches, regimes and landscapes, for studying change (Hofman and Elzen 2010, Smith et al 2010, Geels, 2011). New technologies usually start to develop in niches where specific advantages makes them competitive (e.g. solar PV on sailing boats or in remote off-grid areas). The dominating technical regimes (e.g. technical systems used in industrial sectors) are regarded as very robust due to institutional, social and economic lock-in but can change under pressure either from emerging niche market technologies or from pressure from changes at the landscape level. Changes at the landscape level can be manifested as long-term changing market conditions or changing due to external demands and policy (environmental regulations, energy prices etc.).

The previous 150 years of fossil energy exploitation for developing and powering the industrial expansion can be described as having created a "carbon lock-in" into fossil-energy regimes(Unruh 2000, Foxon and Pearson 2008). Thus, enabling systemic technical change and escaping the current "carbon lock-in" requires not only increased public funding for basic and applied research but also market incentives for creating an enabling institutional environment and overcoming the economic disadvantages and change consumer behaviour (OECD, 2011). The key point here is that barriers for innovation go beyond the mere limitations in technical and economic performances and must be addressed in a systemic way.

With these theoretical frameworks, the role of governments for supporting technical change is widened from pricing the externalities and funding basic R&D (orthodox economic frame) towards a role where the government is allowed to act more as a system enabler. Here, the government will act not only a the landscape level by getting the prices right, but also by actively supporting niche market development of targeted technologies via e.g. market support for new technologies (feed-in tariffs, portfolio standards etc.). Governments can also enable regime shifts by actively building or supporting vital infrastructure such as smart grids, CCS-pipelines, etc.

If the government takes upon a more active role in driving a transition, it must be kept in mind that other actors other than the incumbent firms (e.g. producers of new types of cement, forest industries engaging in biorefineries) have historically been important for enabling long-term radical change. The role of external actors enables a change in current views on what possible futures and pathways may look like. However, it is also recognised that changes can occur at regime level before niche-markets or niche-technologies exist, e.g. through sustainability goals or the recognition of corporate responsibility within incumbent firms (Geels and Schot, 2007). A multi-level perspective analysis on radical change in the basic industry have noticed that for the steel industry there are yet no external actor that could drive technical change (Nikoleris et al 2012).

There are good examples for policy induced technical change in the field of climate change technologies and arguments for the need of technology-specific interventions for further technological change. The so far successful global development in renewable energy technologies demonstrates both the necessity and the ability for directed technology policies for fostering technical change. Several renewable and fossil free energy technologies have reduced their cost substantially the last 10 years and are within reach of becoming price competitive with fossil alternatives on a broad base[26] within the coming 8 to 15 years (IPCC SREEN 2011). This development of renewables have been enabled by more than 30 years of targeted basic and applied research, demonstration programs and, not the least, targeted early market incentives in the form of feed-in tariffs, tax incentives, renewable energy portfolios, etc., all implemented within comprehensive climate technology policy frameworks (Wilson and Grubler 2011).

[26] Several fossil free technologies are already competitive in niche markets, e.g. wind power in good locations, off-grid solar power, ethanol from sugar in Brazil, etc.

9 Governing a long-term transition for a decarbonised industry

Reducing emissions to zero by 2050 or soon thereafter may seem like a daunting task. However, major technology shifts and transitions in industry have occurred before. Examples include the shift from open hearth to basic oxygen furnaces in the iron and steel industry, and from batch digesters to continuous cooking in pulp mills, or the conversion to chlorine-free bleaching. Cost reductions, productivity and quality improvements, but also regulation and consumer demand have been important drivers behind such changes. In addition, economies of scale have driven some of the structural change towards fewer and larger plants and mills. Competition has been a driver of specialisation into speciality steels or other high quality segments in some industries. Although the capital intensity of basic industries may lead us to assume that change and emission reductions is difficult in this sector, history shows that it is constantly evolving.

Now, industry must evolve towards zero emissions and the question is how a transition to decarbonised basic industry may unfold and how it can be governed. Technology development, market changes and other factors will continue to shape the development in industry, only now it must evolve under very strict environmental constraints. Governing the decarbonisation of industry is a different task than regulating and providing incentives for pollution control and reducing air and water emissions. Decarbonisation of industry will affect the core processes in a sector that is at the same time exposed to fierce global competition.

Any purposeful steering of industry emissions requires direction, which in turn requires a long-term vision, despite the inherent uncertainties in technology, market and other developments. From a long-term vision of “decarbonising industry by 2050”, both a strategy for technology development and a strategy for policy development should be outlined. In chapter 9.1 we outline a technology strategy and in the section that follows (9.2) we discuss some basic governance and policy strategy implications, given the limitations set by global, regional and national frameworks for fostering such a technical transformation.

9.1 A technology strategy for decarbonising industry

A technology strategy aims at identifying ways of combining new technical systems, identifying possible multi-purposes technology areas and infrastructure needs and other barriers for future deployment. More comprehensive and in-depth roadmaps for specific technologies in different subsectors (see e.g. IEA ETP 2012) are necessary in order to arrive at a clearer picture of potential transition paths.

A technology strategy for the industry needs to consider the development (i) at the energy system level such a decarbonised power and supply of sustainable biomass, (ii) the needs for basic infrastructure such as CCS, hydrogen and smart grids, and (iii) the development of several targeted technologies. Changes at the energy system level also include future integration of the industry into the energy system (IPCC SRREN 2011).

The high-energy intensity of basic industries, and thus the need to purchase large amounts of energy, means that decarbonisation will have to rely on the availability of energy carriers from carbon neutral sources (e.g., renewable or nuclear energy). The power system is generally expected to be the backbone of future sustainable energy systems. The versatility of electricity, and that this energy carrier in itself does not contain carbon, implies that electrification will be an important strategy. The basic characteristics of some industrial processes and the limited range of energy sources and carriers available means that the technology options in most cases can be narrowed down to only a few ones.

There are some changes in the energy systems that need consistent and continued support. Decarbonisation relies on electrification of some industrial processes and this is dependent on a major supply of CO_2 free electricity. In Sweden, this is within reach given the already high share of renewable electricity and by the host of renewable power technologies expected to enter the market within a decade or two. The higher variability of renewable sources, notably wind in the future Nordic system, means that industry may deploy a mix of electricity and "stored electricity" as hydrogen or other fuels. Such storage options, as well as other approaches to load management, are likely to become more important in industry. The second energy system level "leg" in a decarbonised system is the use of sustainably harvested biomass. Due to the complexity and diversity of biomass resources, it is very difficult to devise clear strategies in this area, e.g. concerning which biomass fractions to use where and for what purpose or combination of purposes: power, heat, biofuels, chemicals, materials, etc. Sweden is relatively well endowed with biomass resources, the basis for a large forestry industry, and must take care that this resource is used sustainably and wisely.

Industry can be expected to become a much more integral part of future energy systems. Options for more flexible demand have been mentioned above, making industry an important actor in future 'smart grids'. One major industrial facility can offer more load management capability than many thousands of households. Industry is already an important power producer and may look for ways of becoming a more flexible producer in the future, whether in biorefineries or other types of plants. Industry is also an important source of low-grade heat for district heating system. Industry could, in the future, become an important actor in the development of hydrogen infrastructures.

For CCS to play a role, first of all the legal situation and development and reliability of CCS itself needs to be proven and accepted. Transport of CO_2 needs to be resolved and supported, which means the legal and economic framework for pipeline transport needs to be clarified. Also, legal responsibility and scientific knowledge regarding potential storage sites needs to be developed. The basic industry, however, is likely to be a follower rather than a leader in the development of CCS.

There are several general technologies that would benefit many industries. The need for continued development of energy efficient processes and technologies, e.g., efficient motor drives, fans, and pumps, is widely recognised. Our analysis indicates that the development of several other general purpose or multipurpose technologies would also benefit industry, as well as society at large. Electro-thermal technologies and electrolytic processes can perform a wide range of tasks in industry based on potentially carbon neutral electricity. Co-electrolysis of CO_2 and H_2O is a potential source of carbon neutral hydrocarbons (perhaps expensive compared to direct use of electricity, but very useful in some applications). Thermo-chemical conversion of biomass (thermal gasification) is another technology that could benefit the decarbonisation of several industries and the energy system as a whole. The development of biochemical conversion routes via enzymatic hydrolysis, fermentation, and various biocatalytic processes would yield benefit to several industries. Electrowinning for the steel industry and the development of inert anodes for the aluminium industry are other important technologies as they target major emission sources with few other zero emission alternatives.

Whereas governments are generally wary of “picking winners”, the specifics of basic industry conversion processes (e.g., reducing iron ore) and the characteristics of energy supply and energy carriers, means that a relatively limited menu of technology options is clearly identifiable. Assuming that zero emissions are indeed the target, these options should be vigorously pursued.

9.2 A policy strategy for decarbonisation

Policy and governance strategies are difficult to devise in any detail due to numerous uncertainties ranging from technological progress to the development of international climate policy regimes and carbon pricing.

The aim of developing a policy strategy is to agree on a broader concept of governance and to outline the role that is appropriate for government to take in a transition towards decarbonising industry. Several policy challenges needs to be dealt with. For example, if government chooses a more proactive role, the conflict between maintaining integrity versus co-operating with business with the risk of regulatory capture needs to be acknowledged and addressed. Further, supporting transitions highlights that policies should not be analysed as single actions but embedded in a broader policy package. In an uncertain future, governments support specific technology systems needs to balance between being adaptable and predictable. Although roadmaps and RD&D-strategies can be developed and implemented in the short term, wide scale deployment of new basic industry process technologies is likely to require high carbon prices (through taxes or trading schemes). In the absence of such conditions, policy strategies must consider other options such as regulatory approaches and permitting procedures, investment grants and subsidies, border adjustment taxes, and sectoral agreements.

A shared vision of decarbonising industry is a first step for discussion. In contrast to other sectors, one observation is that there are yet no shared visions of how innovative technological solutions can contribute to a transition in basic industries (Nilsson et al 2011). Studies on the power sector have shown that long-term emission reduction target may have a more important role in spurring innovation than market-based policies although a carbon price may function as a basic demand-pull (Rogge and Hoffman 2010; Schmidt et al 2012). A shared vision need not to focus solely on decarbonisation but should also be aligned with long term ambitions for competitiveness and business opportunities.

Based on a long-term vision for decarbonising industry, a first step towards thereafter unfolding an industrial transition policy is to develop roadmaps for each subsector, engaging the actors identified above in this process. It may also give input for long-term investment strategies as well as identifying short-term R&D priorities and other joint undertakings that can be shared by public and private funding. The overall purpose of a roadmap is to establish priorities on RD&D, co-ordinate various actors create networks and institutions for knowledge sharing, and map out possible technology and policy pathways. This aims at building confidence and reducing the risk for all actors involved. Roadmaps need to be developed for each subsector due to the differences in technology characteristics as well as the structure of the socio-technical systems at large. Such differences imply a need for R&D, innovation and industrial policies that are adapted to the different technology characteristics, as well as the specific conditions of the subsectors. There are also crosscutting technologies and inter-linkages between industries that could motivate efforts with a broad scope. Due to uncertainty, changing conditions and the unpredictable nature of technology development, the roadmap should not be a static document but rather an on-going process and a process open to new actors. In line with the more general policy discussion above we can make some first observations and suggestion on improved policies below.

One approach to reduce the political and technical risk of making large-scale investments in demonstrations and new plants may be "long-term development agreements" between government and industry. Policy strategies need to consider also the scale of support and different geographical scopes. As an example, for steel industry, a continued EU wide program for ULCOS but with a renewed focus also on the truly zero emitting options would be a good start. In the EU, state aid rules must be adjusted to allow for motivated investment support. The development of inert anodes for the aluminium sector seems suitable to pursue on a global level. From a Swedish and Nordic perspective, the development of technologies for bio-resources may motivate a stronger focus on national or regional co-operation and support schemes.

Investments in new technologies that change the core process of manufacturing basic materials are capital intensive and involve considerable risks for industry. Extensive public-private collaboration on research, development and demonstration is therefore needed. Due to the scale of investments in basic industry, such a system may be modelled on the European Union NER300 scheme where revenues from the EU ETS will be used to fund, for example, CCS and large scale renewable energy demonstration projects. Similar financing mechanisms, in EU-wide or global agreements, may be needed for large-scale demonstrations of new basic industry processes. Intensified R&D efforts, perhaps including such efforts undertaken through the EU EIT KIC (Knowledge and Innovation Community) scheme in other areas, are also important.

Our analyses suggest that targeted support for specific technologies is necessary. The support needs to include funding for RD&D but also for market development support in a broad sense. So far, this approach has worked well in the renewable energy sector through the use of various support schemes (e.g., feed-in tariffs, quota systems, and adaptation of legal structures). The development of renewable energy technologies has succeeded partly due to the long-term stability of the rationales for supporting these technologies (oil crises and energy independence, air pollution and now climate change and energy security again). The renewable technologies that have developed successfully so far are modular technologies that can be demonstrated and deployed in relatively small scale (e.g., PV modules, wind power and ground source heat pumps).

A transition to a decarbonised industry will increase energy and process costs substantially compared to fossil and CO_2 intensive alternatives. A relatively high price on CO_2 will thus be necessary in 2050 for ensuring the transition. A clarification of how the EU ETS will develop up to 2050 and how the EU will ease the effects or avoid carbon leakage would benefit the development. Free allocation helps but we have previously pointed to the possibility of broadening the scope and look at policy responses on the trading arena. Also, a clear message from the on-going climate negotiations on the future interpretation of the burden sharing principle would help (although not likely the coming years). However, regardless of these possible improvements on the global and regional policy level, there is still room for policy initiatives on the national level.

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