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Comparative analysis of options and potential for emission abatement in industry – summary of study comparison and study factsheets

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Comparative analysis of options and potential for emission abatement in industry – summary of study comparison and study factsheets

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Abstrakt

Die Europäische Union hat angekündigt bis 2050 ihre Treibhausgasemissionen um 80 bis 95% zu senken. 2011 wurde dazu die EU low-carbon economy Roadmap der Europäischen Kommission veröffentlicht. Außerdem haben verschiedene Industrieverbände auf Einladung der Kommission eigene sektor-spezifische Roadmaps entwickelt und veröffentlicht, die sich im Detail und aus Sicht der Industrie mit dem Minderungspotenzial in einzelnen Industriesektoren befassen. Zu den Verbänden, die eigene Sektor-Roadmaps vorgelegt haben gehören der Europäische Stahlverband EUROFER, der Europäische Zementverband Cembureau, der Verband der europäischen Papierindustrie (CEPI), und der Europäische Verband der Chemischen Industrie CEFIC. In den letzten Jahren wurden auch vermehrt wissenschaftliche und Studien mit politischen Vorgaben veröffentlicht, die sich mit der Frage beschäftigen wie der Industriesektor langfristig dekarbonisiert werden kann. Diese Studien können hinzugezogen werden, um die von Industrieverbänden vorgelegten Studien in Perspektive zu setzen und die Ergebnisse kritisch zu hinterfragen. In diesem Bericht werden die wichtigsten Annahmen und Kernaussagen der Roadmaps sowie inhaltlich verwandter Studien vorgestellt. Das Ziel ist dabei eine transparente Aufbereitung der verschiedenen Dokumente zur Verfügung zu stellen und damit eine transparente Diskussion über die langfristigen Vermeidungspotenziale in der Europäischen Industrie anzuregen. Dazu werden die absoluten und relativen Minderungspotenziale, die wichtigsten Annahmen hinter den Szenarien sowie eine erste vorsichtige Abschätzung der Auswirkungen der Annahmen auf die Ergebnisse dargestellt. Dadurch soll das allgemeine Verständnis über die Studien und ihre Ergebnisse sowie die treibenden Faktoren dahinter gesteigert werden, Ähnlichkeiten und Unterschiede in den Ansätzen und Ausführungen aufgezeigt und mögliche Differenzen in den Vermeidungspotenzialen in den verschiedenen Studien erläutert werden. Darüber hinaus bietet dieser Bericht einen Überblick und Startpunkt für eine Auseinandersetzung mit den einzelnen Studien. Für ein vertieftes Verständnis der Studien sowie weitere Analysen, Vergleich und Bewertungen der Studien sei der Leser auf die Studien selbst verwiesen. Die in diesem Bericht zur Verfügung gestellten Ergebnisse der Studien können darüber hinaus für eigene Analysen verwendet werden.

Abstract

The European Union has set itself the target of reducing emissions by 80 to 95% by 2050. As a basis for this target, the European Commission prepared and published the EU low carbon economy (EU LCE) roadmap in 2011. In addition, the Commission encouraged industry organisations to prepare sector-specific roadmaps that address the European low carbon ambitions. Several of them, such as the European Steel Association EUROFER, the European Cement Association Cembureau, the Confederation of European Paper Industries CEPI and the European Chemical Industry Council CEFIC, have published such sector-specific roadmaps. In recent years, several scientific and policy-driven studies have also been published that deal with the question of long-term mitigation potential in industry. These latter studies allow us to put the industry roadmaps into perspective and critically reflect their results. This report presents the main results and assumptions of these roadmaps and of a selection of closely related studies. The aim of the report is to provide a transparent compilation of these documents, and thereby increase transparency for the discussion of long-term abatement options in industry in the EU. Our report presents the selected studies with respect to the absolute and relative size of the abatement potentials identified, the assumptions that have been made, and a first assessment on their impact on the results. The idea is to increase the general understanding of what is driving the results, identifying differences and similarities in the approaches and storylines and to explain possible differences in the reduction potentials identified in the different studies. This report further presents to the reader an overview as well as an access point to the different studies. For in-depth understanding and further analyses and comparisons and assessment of the studies, the reader is referred to the documents underlying this analysis and invited to use this study's output as a basis for further work.

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List of abbreviations

BCG	Boston Consulting Group
BECCS	Bio-energy carbon capture and storage
CBA	Cost-benefit analysis
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Usage
CEFIC	The European Chemical Industry Council
CEPI	Confederation of European Paper Industries
ETS	Emissions Trading System
EU LCE	European Union Low Carbon Economy
GHG	Greenhouse Gases
NIR	National Greenhouse Gas Inventory Report
UNFCCC	United Nations Framework Convention on Climate Change

Introduction

In the context of developing strategies to reduce greenhouse gas emissions and fight climate change, the European Union has set itself the target of reducing emissions by 80 to 95% by 2050. As a basis for this target, the European Commission prepared and published the EU low carbon economy (EU LCE) roadmap in 2011. In addition, the Commission encouraged industry organisations to prepare sector-specific roadmaps that address the European low carbon ambitions. Several industry organisations such as the European Steel Association EUROFER, the European Cement Association Cembureau, the Confederation of European Paper Industries CEPI and the European Chemical Industry Council CEFIC have presented their own views on GHG mitigation options in sector-specific roadmaps. In recent years, several scientific and policy-driven studies have also been published that deal with the question of long-term mitigation potential in industry. These latter studies allow us to put the industry roadmaps into perspective and critically reflect on the key results.

This report presents the main results and assumptions of these roadmaps and of a selection of closely related studies. The aim of the report is to provide a transparent compilation of these documents, and thereby increase transparency for the discussion of long-term abatement options in industry in the EU. Our report presents the selected studies with respect to the absolute and relative size of the abatement potentials identified, the assumptions that have been made, and a first assessment on their impact on the results. The idea is to increase the general understanding of what is driving the results, identifying differences and similarities in the approaches and storylines and to explain possible differences in the reduction potentials identified in the different studies. It is not the aim of this study to present an in-depth analysis of each individual study and a full critical evaluation of their methods and assumptions. While highly desirable, such an undertaking is beyond the scope of this project. This report, however, presents to the reader an overview as well as an access point to the different studies. For in-depth understanding and further analyses and comparisons and assessment of the studies, the reader is referred to the documents underlying this analysis and invited to use this study's output as a basis for further work.

The studies and analyses in this report focus on sector studies for emission and energy intensive industrial sectors (iron & steel, pulp and paper, chemicals, cement, lime, ceramics, aluminium).

The report is structured as follows: In section 1, we present the studies selected for this report and the indicators used to describe the studies. In section 2, we present a comparison of the mitigation potential identified in the different studies and provide the studies' (and their core scenarios') main characteristics. We highlight the main insights from the analysis and draw recommendations for future research on deep decarbonisation in industry. The remaining appendices provide detailed information on the studies analysed in this report. This supplementary material includes study factsheets for all studies included (Appendix 1) as well as a table with important information for all scenarios we considered during the process of writing this report, a summary table on the technologies relevant for the different sectors mentioned in the studies, and additional methodical information on calculations that we made (Appendix 2).

1 Selection of studies and key aspects for the comparison

The industry-sponsored sector low-carbon roadmaps for energy intensive industries – i.e. the main industrial sectors covered by the EU ETS - were the starting point for this study. Our main aim was to provide an overview on the mitigation potentials presented within the sector low-carbon roadmaps. For a first classification of the sector roadmaps' results, the EU low-carbon economy (EU LCE) roadmap presented a good reference point. However, some challenges became apparent when we considered the studies in more detail. First, the EU LCE roadmap does not provide detailed information for individual industry sectors. Hence, a comparison on the level of individual industry sectors was not possible. Second, the levels of detail and transparency between studies differ significantly for the different studies. Third, even if all necessary information was provided within the studies, underlying assumptions differ, making a comparison difficult.

In the process of the first analyses, we therefore decided to bring in more studies to provide a more complete picture and put the industry sector roadmaps into perspective. The selection of the additional studies followed the idea to overcome the challenges mentioned above. More specifically, a sector-specific comparison should be possible, leading to the decision to include other sector studies. In addition to the industry-sponsored sector roadmaps, other studies less likely to follow industry interests were included. Assuming that the industry-sponsored sector roadmaps paint a more conservative picture, the full range of anticipated mitigation potentials should be taken into account by including studies from other – scientific and policy-related - sources. Finally, there is a focus on studies developed on the European level. Because of these considerations, the following studies were included in the present analysis:

- EU LCE roadmap and analyses of the EU LCE roadmap:
    1. EU Commission (2011a, b): A Roadmap for moving to a competitive low carbon economy in 2050 ("EU Low-carbon economy roadmap",) & Impact assessment: A Roadmap for moving to a competitive low carbon economy in 2050
    2. Fraunhofer ISI (2012): Concrete Paths of the European Union to the 2°C Scenario: Achieving the Climate Protection Targets of the EU by 2050 through Structural Change, Energy Savings and Energy Efficiency Technologies
    3. Fraunhofer ISI (2014): Study evaluating the current energy efficiency policy framework in the EU and providing orientation on policy options for realising the cost-effective energy efficiency/saving potential until 2020 and beyond

- Further non-sector specific studies:
- BMUB (2015): Climate Protection Scenario 2050 – Second Round
- DECC (2015): Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050 – Cross Sector Summary
- UBA (2014): Germany in 2050 – A greenhouse gas-neutral country
- Wyns and Axelson (2016): The Final Frontier – Decarbonising Europe's energy intensive industries
- Industry-sponsored sector roadmaps and other sector study
- Steel:
- BCG (2013): Steel's contribution to a low-carbon Europe 2050
- Climate Strategies (2014): Carbon Control and Competitiveness Post 2020: The Steel Report
- JRC (2012): Prospective Scenarios on Energy Efficiency and CO_2 Emissions in the EU Iron and Steel Industry

- van Ruijven et al. (2016): Long-term model-based projections of energy use and CO_2 emissions from the global steel and cement industries
- Pulp and Paper:
- CEPI (2011): 2050 Roadmap to a low-carbon bio economy
- Chemicals:
- CEFIC (2013): European chemistry for growth – Unlocking a competitive, low carbon and energy efficient future
- Cement:
- Cembureau (2013): The role of Cement in the 2050 low carbon economy
- Climate Strategies (2014): Carbon Control and Competitiveness Post 2020: The Cement Report
- IEA (2009): Cement technology Roadmap 2009
- Ceramics:
- Ceramie-Unie (2013): Pacing the way to 2050
- Lime:
- Ecofys (2014): A competitive and efficient lime industry
- Aluminium:
- EAA (2012): An Aluminium 2050 roadmap to a low-carbon Europe

More precisely, not only the above mentioned studies but, as far as possible, all scenarios provided within those studies were included in the scenario overview.

Note: Since the completion of this report's analyses, more research has been done that addresses the topic of decarbonisation in industry. In contrast to many of the industry-sponsored sector studies analysed in this report, BDI 2017 covers all sectors, along with decarbonisation pathways for Germany of 80 and 95% compared to 1990. An inclusion of the BDI study along with – if available - other newer studies in future research is recommended.

The aim and focus of the included studies differs significantly, complicating their comparison. To harmonize and limit the length of the analysis, we focused on GHG emissions and emission reductions in 2050 (but state them also for 2030 where available). In general, 2050 allows for more flexibility of the system and hence for more profound changes. Also, the EU low-carbon roadmap as well as the industry roadmaps looked at 2050. However, we also included information on 2030 where available to show not only the target year, but at least one additional step along the reduction path.

As GHG emissions and emission reductions themselves are not sufficient to fully understand the various scenarios, we also included additional information. Information on the scope of the study, e.g. regional and GHG coverage, base year and coverage of NIR[1] sector emissions, helps to provide an overview on the coverage and system boundaries of the study and hence the reduction potential included in, or excluded from, the analysis. In addition, key assumptions underlying the scenarios were collected. That includes a general assessment of the rationale behind the scenario (e.g. economic or technical limits), the inclusion of which technologies (inclusion/exclusion of CCS, inclusion/exclusion of breakthrough technologies), CO_2 prices, production levels, and energy prices. These key assumptions further help to assess and compare the results of the different studies.

The following indicators are included in the scenario overview:

- GHG emissions and GHG reductions compared to 1990 levels in 2030 and 2050 where available

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[1] National Greenhouse Gas Inventory Report, contains information on Kyoto and non-Kyoto GHG emissions as reported under the UNFCCC

- Scope of the study including GHG coverage (CO_2, non-CO_2 gases), geographic coverage, emission base year, coverage of NIR sector emissions, GHG emissions in 1990 (where reported)
- Key assumptions on scenarios including the key rationales behind the scenarios (i.e. economic or technical limits), inclusion of technologies (standard, standard with CCS, breakthrough), assumed production levels, assumed carbon prices, assumed energy prices

2 Scenario overview and comparison

2.1 Highlights

1. **Comparability of studies is limited due to missing transparency and differences in assumptions and modelling framework.** Our in-depth work with the studies, and preparation of study assumptions and results has made clear the fact that comparability of studies is very limited. Significant differences exist in basic assumptions such as technology availability, development of production, coverage of GHG emissions and NIR sectors. Moreover, some studies provide little background information on what has been assumed concerning the development of production, energy efficiency, prices, technology or other factors that impact emission development, making it even more difficult to interpret the study results and compare them with other studies.
2. **Comparison shows significant differences in level of ambition between industry-sponsored roadmaps and EU low carbon economy roadmap.** In total, this comparison of the EU LCE roadmap with industry-sponsored sector studies on emission reduction potentials in industry shows a significant gap in the indicated level of ambition. None of the industry-sponsored sector studies analysed here indicate the availability of large abatement potentials required to fulfil the EU LCE roadmap.
3. **Sector comparison also shows significant differences in level of ambition and costs between industry-sponsored roadmaps on the one hand, and studies from the policy arena and scientific community on the other.** In most sectors, emission reductions reached in the industry-sponsored roadmaps are at the lower end of the studies analysed. Moreover, even with the inclusion of CCS technology, most industry roadmap scenarios reach lower emission reductions compared to other studies included. At the same time, scenarios in the industry-sponsored sector roadmaps require significantly higher CO_2 prices and emphasize the large uncertainties related to CCS and other breakthrough technologies.
4. **Mitigation ranges within a study can be large depending on assumptions and technology availability.** Several sector studies provide a number of different scenarios, showing various possibilities of future developments, e.g. for technology availability, production levels or CO_2 prices. Emission ranges between scenarios are often significant, reflecting the high uncertainties underlying the scenarios up to 2050. Therefore, most ambitious scenarios do not indicate any prices and are often based on technological potentials rather than being price-driven. Where prices are reported, wide ranges for CO_2 prices reflect the substantial uncertainty regarding not only availability but also the costs of tapping substantial mitigation potentials
5. **CCS is a key technology in many studies –– industry-sponsored and policy studies alike – for reaching ambitious emission reductions, but technological uncertainty is high.** Only few studies reach emission reductions of more than 50% without CCS, namely UBA (2014), BMUB (2015) in the CS 80 scenario, and van Ruijven et al. (2016) in the scenarios excluding CCS. Almost all studies include at least one scenario with CCS technology available. In most studies including scenarios with and without CCS, reduction levels reached in the scenarios including CCS are significantly higher compared to scenarios without CCS availability. At the same time, all studies point out that it might be difficult to implement CCS because of high costs and uncertainties concerning commercialization (realization, scalability of reduction option) and acceptance problems. Uncertainty not only relates to CCS but also to other innovative technologies.
6. **Cross-sectoral energy efficiency options along with production decreases are limited in industry-sponsored studies.** While some of the general studies (i.e. not limited to one sector) highlight cross-cutting energy efficiency options (e.g. energy-efficient lighting) as an important part in reaching low emission levels, industry-sponsored studies focus largely on existing and innovative process technologies, which still need to reach maturity and economic viability. Also,

while production decreases would lead to reduced emissions, that is not the way chosen in the industry-sponsored sector roadmaps. In contrast, ambitious reduction scenarios in several non-industry-sponsored studies analysed in this report mostly assume either constant production levels or even production decreases in their scenarios. Assumptions on physical production in the EU LCE roadmap are unknown. A detailed comparison on assumed production development between the studies in this report is not possible due to a lack of sufficiently detailed data.

2.2 Comparison of mitigation potential in industry

The comparison focuses on how the abatement potentials identified within industry-sponsored sector studies compare with the reduction targets analysed in the EU LCE roadmap and how they link to other studies included in our analysis. A number of methodological issues have to be overcome. The first problem in the comparison is that the EU LCE roadmap does not give many absolute numbers for CO_2 emissions or reductions in Mt CO_2eq. Rather, the study indicates the emission development as an index or gives percentage reductions in annual emissions in 2050 compared to the annual emissions in 1990.

The EU LCE roadmap is based on the EU Energy Baseline from 2009 (COM 2011c), in which industrial energy related emissions are given at 781 Mt CO_2eq. In addition to energy related CO_2 emissions, non-energy related CO_2 emissions ("process emissions") as well as non-CO_2 GHG emissions are also listed in the EU LCE roadmap, but non-CO_2 emissions are not differentiated by sector. For the comparison, we therefore concentrate on CO_2 and add energy related CO_2 emissions and CO_2 emissions from industrial processes from the EU LCE roadmap, giving a total of 1,111 Mt CO_2eq. This figure is roughly comparable to the sum of the direct 1990 emissions in the analysed industry sector roadmaps (for which we calculate a total of 866 Mt CO_2eq.), given the fact that we cover only the largest emitting sectors. An even better match is reached when comparing this sum with LCE roadmap emissions for energy intensive industry (EII) only, which we calculate as 880 Mt CO_2 from the available data in (COM 2011c). In both our calculations, based on official UNFCCC inventory data (EEA 2016) as well as in the sector roadmaps, the refineries are not included.

Another challenge arises from the differences in ambition levels. The EU LCE roadmap envisages a reduction of annual industrial emissions by 83 to 88% in 2050 compared to 1990. Similar reductions in the sector roadmaps are only present in those scenarios where ambitious assumptions on technology are made, i.e. those scenarios including either CCS or other breakthrough technologies.[2] In the majority of the scenarios depicted in the sector roadmaps, relative reduction is much lower than 80% and the sum of emissions for 2050 in the sector roadmaps is much larger than emissions targeted in the EU LCE roadmap (see Figure 1). Looking only at the most ambitious scenarios in the industry-sponsored roadmaps covered in our analysis, these add up to emissions of 295 Mt CO_2eq. in 2050, which is more than double the target for the industrial sector in the EU LCE roadmap (119 Mt CO_2eq.) - see the right column. The less ambitious scenarios of the sector roadmaps lead to annual emissions of roughly 650 Mt CO_2eq. in 2050, which is similar to the baseline development of emissions from energy intensive industries in the EU LCE roadmap (590Mt CO_2eq.) – see the middle column. Looking at the relative reductions presented in the sector roadmaps (see Figure 2) it can be seen that none reach 80%. Cement and ceramics in the scenarios with the highest reduction come near 80%. For chemicals the results are in the order of 70% and for iron & steel they are below 60% in the BCG roadmap. Looking at the sector roadmaps' less ambitious scenarios, none exceeds 60%; for iron & steel, cement, chemicals and lime they are even below 40%.

In the following sub-sections, we present and discuss the studies by sector: Iron and steel, pulp and paper, chemicals, cement, and aluminium. Additionally, the aspects energy efficiency, CCS, changes in

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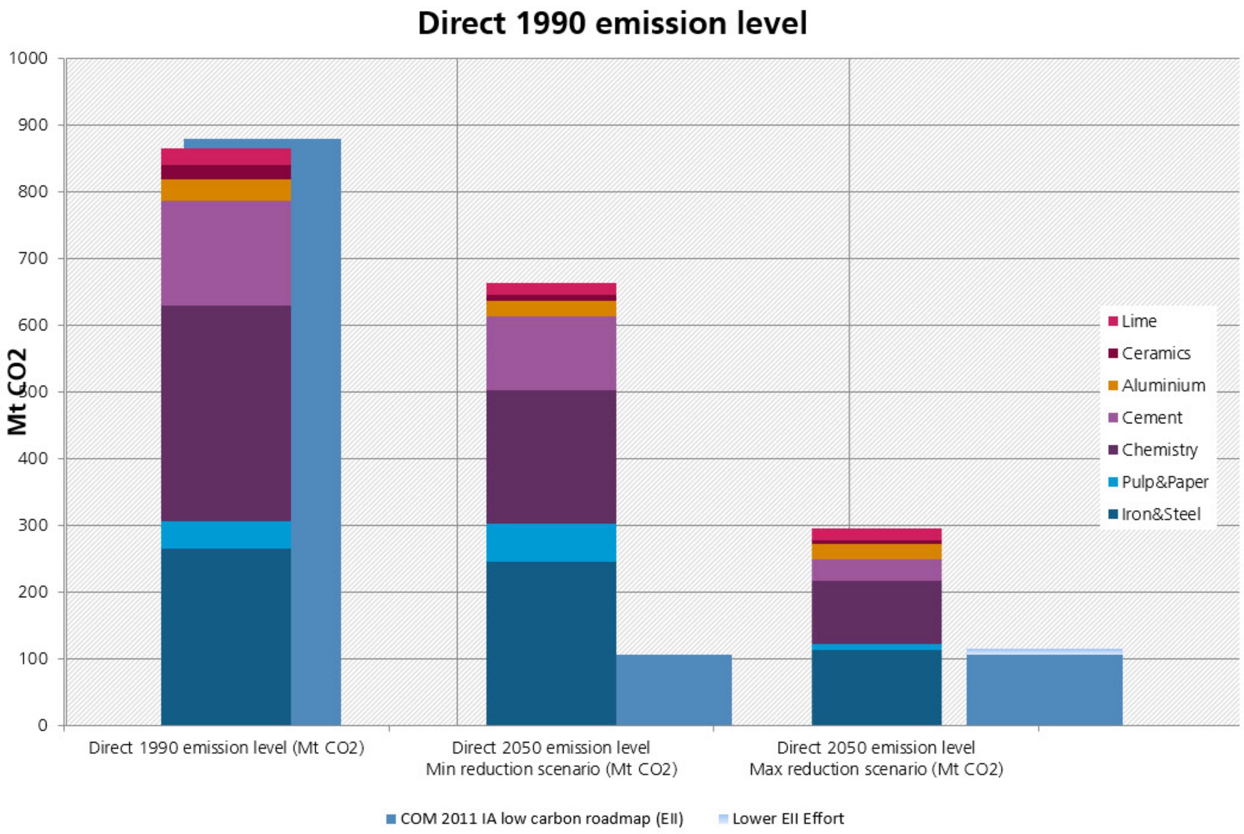
[2] One scenario in which a drop in production is assumed also achieves similar reductions.

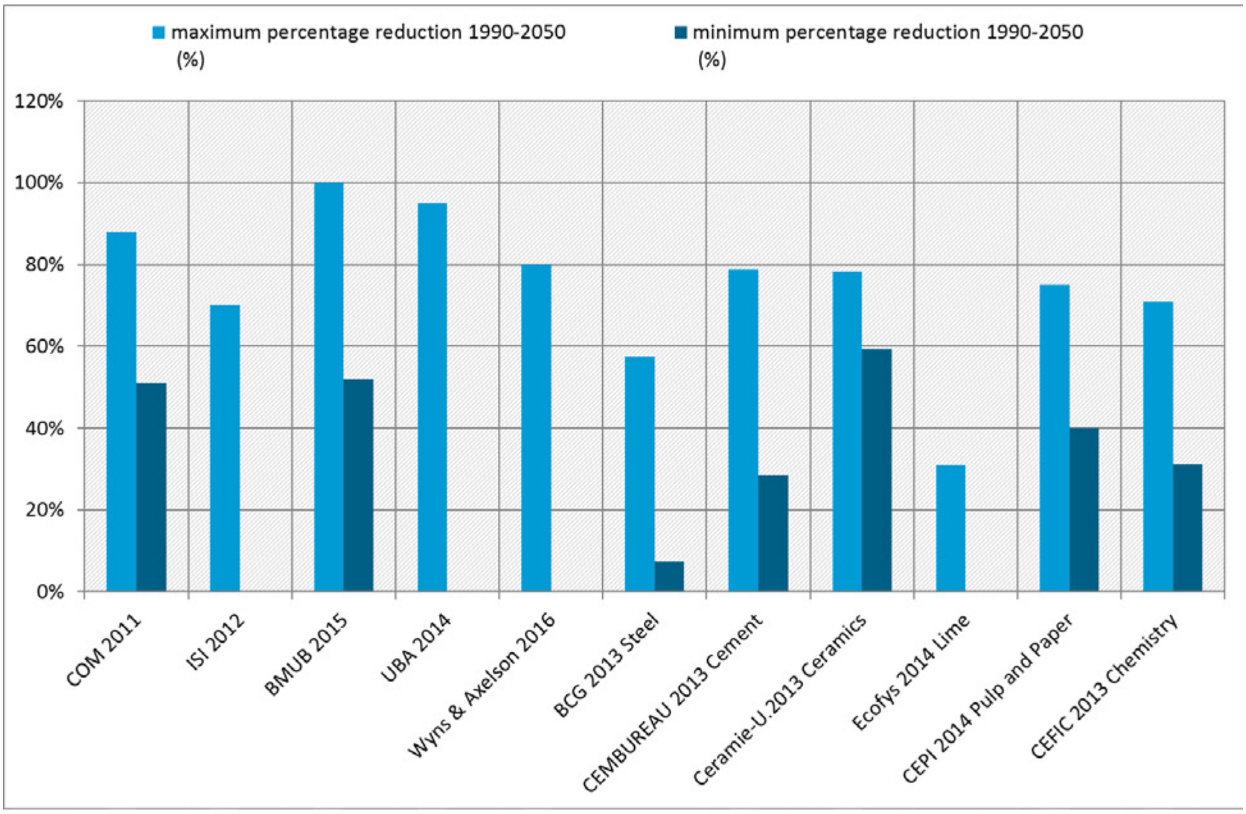
fuel mix and CO_2-prices are discussed across studies to understand which roles they play for the results. Supplementary material on the scenarios and studies analysed can be found in section 3. A summary table of the scenarios considered, at the end of this section, provides information on the reduction ranges. The table covers not all scenarios, but highlights the key scenarios and reflects the reduction ranges available in the different studies.

Figure 1: Comparison of annual emissions 1990 and 2050 in low carbon roadmap and sector studies



Source: own representation based on calculation of direct emissions from the different studies: BCG 2013, CEPI 2011, CEFIC 2013, CEMBUREAU 2013, Ceramie-Unie 2013, Ecofys 2014 (Lime), EAA 2012, COM 2011 (Impact Assessment low-carbon economy roadmap 2050, including reference scenarios as minimal reduction scenario)

Figure 2: Comparison of relative emission reductions in EU LCE roadmap, industry-sponsored sector roadmaps and other studies



Source: own representation based on calculation of direct emissions from the different studies: BCG 2013, CEPI 2011, CEFIC 2013, CEMBUREAU 2013, Ceramie-Unie 2013, Ecofys 2014 (Lime), EAA 2012, COM 2011 (Impact Assessment low-carbon roadmap 2050), ISI 2012, BMUB

2.3 Iron and Steel Sector

The study "Germany in 2050 – a greenhouse gas-neutral country" (UBA 2014) depicts an emission reduction close to 100% compared to 1990 for the iron and steel industry. The only remaining source of emissions is the burning of graphite electrodes in electric arc furnaces (EAF). The study assumes qualitative growth, which is visible in increases of gross value added, with constant production (UBA 2014). In contrast to the other studies, the UBA-study foresees a complete restructuring of the European steel sector. Primary steel production in BOFs does not take place anymore; instead direct reduced iron and a complete shift to EAF steel production characterize the steel sector. Direct reduction of iron, use of renewable methane or hydrogen as well as electricity and increased scrap recycling play a large role. Furthermore, the description of emission reduction strategies includes several options that are not detailed in the other studies: improvements in resource efficiency (material efficiency is also included in the Climate Strategies steel study) and the shortening of process chains as a strategy to improve energy efficiency. Both aspects are not a specific technology but rather a systemic perspective to optimize the steel production and utilization process, requiring substantial structural changes.

The study Climate Protection Scenario 2050 (BMUB 2015) differentiates between energy-related and process emissions. While energy-related emissions are not reported by sector, process emissions are. In the CS95 (95% reduction scenario), process emissions within the iron & steel sector are reduced by 98% between 2010 and 2050, with a slight decrease in production until 2050. The key for reaching those high reduction levels is the use of CCS. The blast furnace-blast oxygen furnace (BF-BOF) steel making process still accounts for around 55% of total steel production in Germany in this scenario, but its share decreases compared to 2010 (70%). Moreover, the combination of CCS with the use of biomass allows an offsetting of other emissions from industry sectors in this scenario. The less ambitious CS 80 target scenario from the same study, paints a different picture. Here, CCS technology is not allowed. As a result, remaining process emissions for the iron and steel industry are still significant, reductions in the same time frame amounting to roughly 60%. In the EMS scenario[3], process emissions are reduced by around 40% between 2010 and 2050. In all three scenarios, the share of BF-BOF is 55%, however, crude steel production is 5% lower in CS 95 compared to the other two scenarios. Compared to 2010 production decreases in all scenarios, by 15% (CS 95) and 8% respectively in the other two scenarios.

Wyns and Axelson (2016) see a reduction of 80% by 2050 compared to 1990 levels as the technical limit for the iron and steel industry. They do not provide further insights on the underlying assumptions for the scenario.

The JRC study (2013) presents scenarios with relative emission reductions in the range of 50% to 55% by 2030. In all scenarios, CCS technology is available. Further, reductions in energy consumption are an important factor for emission reductions. The replacement of natural gas with "syngas" from biomass or charcoal as reduction agent is also mentioned in the study and has been a topic within the ULCOS RD&D project[4]. The JRC study suggests that CO_2 prices alone will not be sufficient to bring about significant reductions in energy demand and emissions in the iron and steel industry. They conclude that technology-push measures are needed to drive the required change since only innovative technologies have the potential to substantially reduce CO_2 emissions. The production levels are assumed to increase by roughly 43% by 2030 compared to 2010. Compared to other studies, growth rates for iron and steel industry are significantly higher in the JRC study.

The Climate Strategies study (CS-IS 2014) on steel points out that energy efficiency improvements allow savings at low cost, but several barriers exist: often the implementation of the measures requires significant time of plant shut down and mobilization of capital and high payback periods are a problem. Overcapacity of total production and low utilization rates as well as low CO_2 prices are further aspects hindering change.

ISI (2012) points to the potential of a more systemic perspective: The study mentions the strip casting process that promises significant energy savings. Instead of re-heating the steel for final shaping, a continuous near net shape casting is attached to the steel production process, reducing the specific energy demand by 75%. Further improvements can be achieved with heat recovery from steel rolling and top gas recycling from the blast furnace.

The setup of the study by van Ruijven et al. (2016) is different. They provide global figures and do not state 1990 emissions. In their scenarios, they reach emission reductions of up to 88% for a CO_2 price of 100$/t CO_2 compared to their baseline scenario. CCS technology allows higher reductions. However, even in scenarios without CCS technology, reductions of up to 80% below baseline are possible by a shift to direct reduction and EAF. It is worth mentioning that the results from van Ruijven (2016) indicate a substantial difference in the fuel mix in the iron & steel sector globally by the inclusion of CCS. In the mitigation scenarios where CCS is not available, coal is phased out while in the scenarios with CCS included, coal will still be the dominating fuel in the most energy intensive sectors globally.

Of the industry-sponsored sector roadmaps for the iron and steel sector, the most ambitious reduction is sketched in the BCG 2013 study as "lower theoretical boundary with CCUS". The scenario achieves a reduction of 58% in 2050 annual emissions compared to 1990 emissions. Concerning energy

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[3] existing measures scenario" – all policies adopted by October 2012 are incorporated in the scenario, reflecting the then current state of the energy and policy framework

[4] Major players such as Arcelor Mittal withdrew from the project in 2012 (see https://in.reuters.com/article/arcelormittal-france-ulcos-plan-idINDEE8B508O20121206). They state this does not mean that the project is abandoned.

efficiency, BCG (2013) in its scenario continued improved efficiency upper boundary – a baseline scenario rather than a policy scenario -, assumes an improvement of efficiency to the average level of the 50% best performers. According to the study, historic efficiency gains led to a 14% CO_2 emission decrease in 2010 compared to 1990 and best performers in the BF-BOF route in the EU are already operating close to the optimum. Additional reductions from efficiency measures provided in the scenario sum up to 4Mt CO_2eq. (1Mt CO_2 in EAF and 3Mt CO_2 from BF-BOF) corresponding to roughly 1.5% of the 1990 direct emission level. Fuel mix changes are not discussed explicitly in the BCG study. However, the technology options considered imply certain changes in the fuels used: the case of the replacement of the BF-BOF routes by a combination of direct reduced iron and its processing in an EAF (DRI-EAF) implies a shift from coal and coke to natural gas (and electricity), which may further be replaced with (renewably produced) methane or hydrogen (UBA 2014). Production in the BCG scenarios increases by 37% compared to 2010 levels in all scenarios but one. Again, availability of CCS technology increases emission reductions significantly.

2.4 Pulp & Paper

UBA (2014) assumes that in the long run the entire energy need for pulp and paper production can be supplied from renewable energy sources since the share of solid fuels is very small, most energy used is gas and electricity and the share of renewable fuels (from the production process) is already relatively high today. They further assume an efficiency increase by a factor of two and an increasing share of recycled fibre use to 83%. As there are no process emissions in the pulp and paper industry, the sector reaches a complete decarbonisation, independent of production levels, which are assumed to remain constant compared to 2010.

BMUB (2015) assumes a share of recycled paper production of 95% in 2050 and a diffusion of several energy efficiency options as well as use of heat pumps and waste heat recovery in the CS 95 scenario. The study does not provide information on fuel mix or emissions of the pulp and paper sector. It can be assumed, however, that fuel used is mainly biomass and electricity and that therefore the sector, despite slight production increases compared to 2010 levels, reaches emission levels of close to zero.

Also the DECC (2015) study reaches emission reductions of up to 97.5% compared to 1990 levels. The main options for emission reduction for its maximum reduction pathway for the pulp and paper sector are industrial clustering and heat networking (26% of total emission reduction), 100% electricity (20% of total emissions reduction), heat recovery on hoods (15% of total emission reduction), improved process control (7% of total emission reduction) as well as impulse drying and waste heat recovery/heat integration (each 3% of total emission reduction). Production is assumed to increase by 1% p.a.

In contrast, the CEPI sector roadmap depicts emission reductions of 75% in 2050 compared to 1990. CEPI (2011) does not give information on production growth. The key aspect for emission reduction in the pulp and paper sector according to CEPI (2011) is improved energy (as well as resource) efficiency. Adoption of Best Available Technologies is expected to reduce emissions by 10Mt, an additional 1Mt is associated with the introduction of infrared dryers. Another lever for emission reduction are changes in the fuel mix contributing 5 Mt of emission reduction in the CEPI (2011) study. Breakthrough technologies are said to achieve 14 Mt of emission reduction. CEPI (2011) points to further reductions in indirect emissions: 5 Mt in transport and 13 Mt from the decarbonisation of electricity

2.5 Chemical Industry

The UBA (2014) study for Germany reaches highest emission reductions with nearly -100% in annual emissions 2050 compared to 1990. This potential includes technologies that are not yet available. The only remaining emissions are 0.5 t CO_2 eq. N_2O emissions from production of adipic and nitric acid corresponding to a reduction in process related emissions of 98.5% (2050 compared to 1990). The energy demand of the chemical industry is assumed to be satisfied entirely from renewable electricity and renewably produced methane and hydrogen resulting in zero energy related emissions. The study assumes that fossil raw materials such as naphta or natural gas can be replaced with renewably produced methane from which then higher carbon hydrates can be synthesized. A direct conversion from carbon dioxide and water to higher carbohydrates is sketched but currently not state of the art. It is further assumed that coal as reduction agent will at least in part be substituted with zeolyth.

Process emissions for the chemical industry in BMUB (2015) can be reduced to below 1Mt CO_2eq. in 2050 by applying CCS. For the less ambitious scenarios that do not include CCS technology, process emissions are between 14 and 11 Mt CO_2eq. in 2050. These reductions are realized despite constant or even slight increases in production levels for the main chemical products.

The UK decarbonisation study for the chemical sector (DECC 2015) in its maximum technology pathway achieves emission reductions of nearly 90%. Biggest contributions come from CCS (combustion, 34%) and biomass as fuel (30%). Energy efficiency (7%), biomass as a feedstock (8%) and CCS for process emissions (ammonia and hydrogen, 9%) account for another quarter.

The scenario of Wyns and Axelson (2016) aims at a reduction of 80% in 2050. This requires breakthrough technologies, new products and feedstocks with innovations in business models and CCS. In the petrochemical industry, bio-based feedstocks play a key role for emission reduction by replacing fossil fuel based feedstock as well as enhanced recycling. A possible conflict over biomass resources might arise if these shall also be used for energy or bio-based fuels. In ammonia and fertilizer production the study states the electrochemical production of ammonia, use of bio-based waste or business model revolutions in the fertilizer industry as important levers to reach ambitious emission reduction.

The CEFIC sector roadmap scenarios lead to reductions between 30 and 70% in 2050 compared to 1990 emissions. These results are associated with CO_2 prices of 53 €/t vs. 273 €/t CO_2eq. CEFIC (2013) presents energy efficiency improvements as the most important lever for further emission reductions. According to CEFIC (2013), the emission intensity decreased by roughly 50% between 1990 and 2010. Further technical efficiency improvements in both electricity and fuel/heat from 2010 to 2050 are estimated to range from 20% to 50% (generic improvement factor for energy efficiency) for different products, with the lower end reflecting that technologies for basic products are already relatively mature while for newer products at the end of the value chain higher improvements are foreseen because innovation leaps are still possible. A further substantial contribution to emission reductions is attributed to changes in the fuel mix for heat generation. Coal is assumed to be completely absent from the chemical industry’s fuel mix after 2030. Natural gas has the largest share (similar to today). Renewable options such as biomass and geothermal energy gain in importance. Information on changes in production are not provided.

2.6 Cement

BMUB (2015) in the CS 95 scenario reaches emission levels close to zero for process emissions from cement clinker by the application of the CCS technology. At the same time, production of cement clinker is significantly reduced compared to 2010, by 28% in the EMS (2012) and CS 80 scenarios and by 42% in the CS 95 scenario. Compared to other studies, BMUB (2015) assumes that a greater reduction of the clinker share is possible (to 61% in the CS 80 or even 52% in the CS 95 scenario). For the less ambitious scenarios, however, process emissions from cement clinker burning are still significant with 9Mt CO_2.

The Wyns and Axelson study on deep decarbonisation states that energy efficiency is not sufficient and sketches some further approaches to reach an 80% reduction in the cement sector compared to 1990 levels. The study analyses CCS and limestone reduction through electrolysis technologies (process innovations), alternative materials to replace clinker and downstream innovations (i.e. innovative technologies to increase material and resource efficiency in the application of cement thereby reducing downstream demand). However, as the study points out, all of these innovations are currently at the R&D stage only so that there is no/little indication on their potential for large-scale commercial application.

Van Ruijven et al. (2016) project a significant emission reduction (37% compared to 2010) due to the increase in biofuel use in the cement sector in Western Europe even in the baseline scenarios.[5] For the most ambitious scenario, they reach a reduction of 80% compared to the baseline scenario (81% compared to 2010). Key for reaching ambitious emission reductions is the availability of CCS. In scenarios without CCS availability reductions below baseline amount to up to 38% in 2050. However, except for CCS no technology is included in the scenario that allows for the reduction of process emissions from the burning of cement clinker. Reduction of the clinker share in cement is included, but limited to 65% or higher. Information on production levels are not provided.

UBA (2014) depicts a 76% reduction in CO_2 emission in the German cement sector without CCS compared to 1990 (70% below 2010),, resulting in 6.3 Mt emissions which are entirely related to the raw materials (UBA 2014, p. 185). The study highlights the production of cements with a reduced clinker share as the currently most effective measure to reduce emissions in cement production. Pointing to estimates from the World Business Council for Sustainable Development, they give - similar to numbers in other cement studies - a clinker ratio of 0.71 for the year 2050. Novel cements are highlighted as another promising route for future emission reduction the cement industry, but today it is unclear which of those technologies will reach a commercial level. A breakthrough in those new technologies would be accompanied by a restructuring of the cement industry. Production levels are constant in the scenario compared to 2010 levels.

CEMBUREAU (2013) sketches a scenario with an 80% reduction largely based on the application of CCS. With existing technologies, CEMBUREAU depicts a reduction of 32% compared to 1990 to be feasible. The main options for emission reduction are fuel switch (replacing traditionally used fossil fuels in particular coal with alternative fuels or biomass) which achieves roughly half of the depicted reductions, a reduction in the clinker-to-cement ratio and improvements in thermal energy efficiency.[6] The study points to the trade-off that often improved thermal efficiency comes at the price of increased electricity consumption. CEMBUREAU also assumes constant production levels compared to 2010.

2.7 Aluminium

UBA (2014) outlines several options for deep emission reductions in the non-ferrous metals industry: increased scrap recycling, tapping remaining energy efficiency potentials, reducing process emissions through the utilization of inert anodes. Citing the IEA, they state that inert anodes might be commercially operated by 2030 thereby avoiding process related emissions in primary aluminium production completely. Further assumptions to reach carbon neutrality in 2050 in the study are a high share of the energy demand covered with renewable electricity (62%) and the remaining part covered with renewable methane.

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[5] In contrast to their results for iron & steel, the existence of CCS is not affecting the fuel mix very much (van Ruijven et al 2016).

[6] In a -80% reduction scenario energy efficiency increases contribute to emission reductions by 4% to 12%. See Figure 3 in CS C (2014), page 10.

BMUB depicts a slight decrease in process emissions from aluminium production[7]. Reasons are mainly the reduction in primary aluminium production with the share of secondary aluminium production increasing to 73% (EMS (2012), CS 80) and 77% (CS 95) respectively. Total production of aluminium slightly increases compared to 2010 levels.

The EAA roadmap (EAA 2012) for aluminium sketches a reduction of 31% in 2050 compared to 1990. The potential for emission reduction with current technologies is said to be realized already, suggesting that innovative technologies are needed to achieve further reductions. The EAA study does give much information on the contribution of individual technologies and does not address the effect of efficiency increases for emission reduction separately. The study mentions the key role of increased recycling as well as new technologies to avoid direct emissions from carbon anode consumption. Further, the study points to downstream emission reductions of 70 Mt CO_2 per annum in other sectors from use of aluminium in transport, due to its lightweight. Further reductions are said to be achieved from the usage of aluminium in packaging, or energy efficient buildings. Information on development of production levels is not provided.

2.8 Cross sectoral mitigation options in the studies

Most industry-sponsored sector studies focus on process technologies and do not pay much attention to cross-cutting energy efficiency technologies (e.g. energy-efficient lighting). In contrast, energy efficiency is important in many of the other studies.

In the reference scenario of the EU LCE roadmap, a decrease in energy intensity (energy demand per value added) of 62% in 2050 compared to 1990 is projected in combination with a decrease in CO_2 emissions of 33% by 2050 compared to 1990. In the decarbonisation scenarios, energy intensive industries are assumed to reduce emissions by 85 to 90% in 2050 compared to 1990 driven by further decreases in energy intensity (-75% in 2050 compared to 1990).

Energy efficiency also plays a major role in the two studies from Fraunhofer ISI et al. (2012, 2014) that also include cross-cutting technologies in industry. Due to their widespread use, they are responsible for a large share of industrial energy consumption and have significant reduction potential. According to Fraunhofer ISI et al. (2014), electric motor systems and lighting make up for more than 70% of the industrial electricity consumption; space heating accounts for around 10% of industrial final energy demand in Europe and steam systems for 20-25%. Both studies particularly focus on the contribution of energy efficiency. Fraunhofer ISI (2014) estimates an emission reduction potential for 2030 of around 50% in the industry sector (compared to1990 levels). It is important to keep in mind that the study includes the entire industrial sector and not only the energy intensive branches that have typically lower untapped energy efficiency potentials.

Also the WEO 2016 foresees a substantial contribution of energy efficiency to emission reduction in its 450 scenario (IEA 2016). In its chapter on energy efficiency, IEA (2016) highlights the importance of motor systems as one cross-cutting technology that accounts for more than 50% of total final electricity consumption and more than 80% of world industrial electricity consumption. They point out the importance of looking at the entire system and not only the motor itself because most efficiency gains are found not in the motor, but in the system. Those measures can be variable speed drives, improvements in system components or optimized management practices. The study emphasizes that, even though system wide measures promise the highest benefits, they are difficult to incentivize.

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[7] Process emissions in primary aluminium production are below 1Mt CO2 eq. in Germany today as well as in the scenario figures for 2050.

The WEO further points to the potential of a more holistic perspective for emission reduction e.g. the more efficient use of products or the role of information and communications technologies (ICT). This is in line with findings from Wyns and Axelson (2016) study, that postulates that energy efficiency increases are not sufficient to reach decarbonisation targets and therefore puts the focus on innovative process technologies along with business model and product innovations.

2.9 CCS

CCS plays a central role in many studies to ultimately comply with ambitious emission reduction targets by 2050. The EU LCE roadmap applies CCS after 2035 in particular to capture process emissions (e.g. in the cement and steel sector). Also the WEO in its 450 Scenario and the BMUB in its CS 95 scenario depict significant contributions of CCS to emission reduction at global level respectively in Germany. However, CCS is an expensive option and as the EU study argues "has no other real benefits than reduced GHG emissions". Competitiveness of industry will likely be affected if they need to achieve the targeted emission reductions by significant application of CCS in a world with fragmented climate policies. CCS would only become profitable at high CO_2 prices or public support would be needed. Under lower reduction requirements, CCS would not become mainstream for industrial process emissions (COM 2011b).

Several of the industry-sponsored sector studies include CCS as one option to achieve the necessary emission reductions to comply with the targets set by the European Commission. However, they are highly sceptical regarding its costs and commercialization, which they typically state will require public support or very high CO_2 prices. The BCG (2013) study assumes that CCS could only be implemented as a joint effort by all industries and public authorities because of the high investments needs. Also in the lime roadmap (Ecofys 2014) and the chemicals roadmap (CEFIC 2013), CCS is mentioned, but its potential contribution is not quantified. In case of the chemical industry, utilizing the captured carbon (CCU) also presents an option, but is not analysed quantitatively. CEMBUREAU (2013) expects costs for CCS to fall substantially, but both, investment and operating costs to remain substantial. CEPI (2011) points out that even though they assume the use of CCS as does the EU LCE roadmap, "a delayed CCS scenario is more and more likely". They also mention bioenergy with CCS (BECCS) as an option for the pulp and paper industry, but do not include it in the roadmap. CEPI (2011) rather argues for focusing on reducing heat demand to cut emissions and investing into the development of breakthrough technologies in this area instead of BECCS.

The WEO (IEA 2016) discusses BECCS as an option to offset emissions from areas that are difficult to decarbonize. They point out that BECCS is an unproven technology so far and that uncertainty does not only relate to the technology per se but also the availability of biomass resources. They investigate the implications of BECCS implementation for possible emission trajectories at global level and find that without the option of negative emissions, emissions need to reach zero 30 years earlier. BMUB (2015) allows for CCS also in combination with biomass, but only in the most ambitious CS 95 scenario. The other scenarios in that study do not include CCS technology as a mitigation option. Fraunhofer ISI (2012, 2014) completely dispense of CCS technology. Neither does UBA (2014) include CCS, inter alia because storage capacity in Germany is too limited.

2.10 Outlook on research on deep decarbonisation in industry

This report presents a systematic overview of assumptions and results along with a first comparison of selected studies addressing emission reduction potential in industry. Due to this limited scope and to avoid further extending its length, the report only presents a first step in generating insights into mitigation potential in industry sectors and leaves plenty of room for further work. Four recommendations may serve as starting points for future analyses:

Recommendation 1: Widen the scope of studies analysed

The studies covered in this report are limited. Moreover, the selection process for inclusion of studies was a sequential one. We started off with industry-sponsored sector studies and the EU LCE roadmap. When it became apparent that that was not sufficient for a comparison as the sector roadmaps are very focused and the level of detail for industry in the EU LCE roadmap is limited, other studies were added. The selection process of those additional studies has a clear German focus. A broader look at studies with more ambitious decarbonisation targets such as Wyns and Axelson (2016), IEA (2016), UBA (2014), BMUB (2015) or negaWatt (2013) indicates several options that could lead to substantial decarbonisation.

In UBA (2014) energy demand and demand for feedstock is nearly completely satisfied from renewables: This requires substantial amounts of renewable electricity and renewably produced methane (as well as a source for carbon to produce methane from electricity). Furthermore, they include options that would imply a restructuring of industries such as a complete switch to EAF based steel production eliminating the need for any plants for oxygen steel production and novel cements which would imply a restructuring of the cement industry.

The WEO (IEA 2016) as well as BMUB (2015) in its CS 95 scenario foresee a substantial contribution of CCS and BECCS. Furthermore, they highlight the importance of cross-cutting technologies and a more holistic approach to emission reduction going beyond the sector level and including aspects such as material efficiency to reduce demand.

Wyns and Axelson (2016) points to process and product innovations, e.g. improved materials to reduce downstream emissions and business model innovations that would give incentives for the implementation of new technologies. Also CEFIC (2013), CEMBUREAU (2013) and EUROFER (2013) point to downstream potentials.

Finally, the French negaWatt study (2013) presents an ambitious decarbonisation scenario that relies only on existing technology and does not even include CCS or nuclear technology. Instead, the study pictures an industrial transformation based on the reorientation of production to genuine needs. This includes e.g. a reduction of packaging by the eradication of advertising fliers but also a strengthening of repair and recycling as well as the end of planned obsolescence.

Turning away from the choice of studies, two main points became apparent in the process of preparation and analysis. First, around the information that could be drawn from the existing studies, the comparison of the different studies shows that a gap exists in level of ambition between industry-sponsored studies on the one hand and many studies from science and policy making on the other hand. This observation suggests two recommendations:

Recommendation 2: Intensify exchange between industry on the one hand and policy makers and scientists on the other hand to increase understanding

Significant exchange is necessary between industries on the one hand and policy makers and scientists on the other hand, to better understand differences between studies. A major difficulty when talking about emission reductions in industry sectors is that the transformation process is still at the very beginning. In contrast, in other sectors such as electricity discussion on reducing emissions started much earlier and hence transformation processes including development of technologies have progressed further. Looking at industry transformation, achieving the industrial emission reduction targets would require ensuring that the abatement potentials are indeed tapped and ambitious technology options are developed and implemented. Development of those technologies and – where reported - related costs are highly uncertain, which is reflected in the varying CO_2 price levels in the studies. Most ambitious scenarios do not indicate any prices and are often based on technological potentials. Moreover, studies often stick to the status quo regarding industry structure, while transformation processes are likely to change existing structures. Exchange between policy makers, scientists and industry is necessary to identify the needs of industry and provide a framework for the transformation of the industry.

Recommendation 3: In-depth analyses at the sector level as well as for cross-cutting topics and systemic aspects are required

Our report only presented a very first, mostly descriptive analysis of the different studies. For an in-depth critical review and a meaningful debate, more in-depth analyses are required. The comprehensive supplementary material provided in this report may serve as a starting point for further analyses. These analyses are needed on a general level as started in this report, but also on a sector level due to the various specific situations and challenges in the different industry sectors.

Second, the lack of detail and transparency along with significant differences in scope and assumptions of the studies significantly complicate working with the studies resulting in our last recommendation:

Recommendation 4: Increase transparency on data and assumptions to increase understanding

To enable in-depth analyses and a meaningful debate between policy makers, scientists and industry, transparency on data and assumptions used within the different studies is key. The different degrees of detail in particular in the sector studies, but also in the other studies makes the comparison difficult. Some studies provide little background information on what has been assumed concerning developments of production, efficiency, prices, technology or other factors that impact emission development. In some studies even information on results is very limited. In this report, we attempted to fill some of the gaps. However, that was not always possible and adds another layer of uncertainty of the analysis. Further studies should therefore try to fill more gaps and thus improve the basic analysis provided in this report.

2.11 Summary table – scenario overview

The following table provides an extract of the scenarios analysed for this study. The scenarios were chosen to represent the reduction ranges covered by the various studies. However, to avoid cluttering we abstain from listing results from very similar scenarios within each study. The ordering of the scenarios follows a simple system: studies are listed from the study with the most ambitious scenario to the study with the least ambitious scenario. Within each study, scenarios are sorted from lowest ambition to highest ambition.

Parts of the table:

- Reference: Indicates source (study) of the scenario
- Scenario ID: name for the scenario within the study
- Scope:
    1. Kyoto GHG coverage: indicates the GHGs covered by the scenario, in most cases either CO_2 only or all Kyoto GHGs
    2. GEO: indicates regional coverage of the scenario
    3. Base Year: indicates base your used for the scenario
    4. Coverage of relevant NIR emissions: indicates coverage of the scenario in relation to reporting under the UNFCCC. The percentage value equals the total amount of emissions covered by the respective study divided by the corresponding NIR emissions for a comparable historical reference year, comparable geographic area and comparable sectors
    5. GHG emissions in 1990: GHG emissions in 1990 for the covered countries for industry sectors included in the scenario
- Results

1. Direct GHG emissions in 2030/2050: as provided in the scenario description or calculated based on information provided in the study
2. GHG reduction in 2030/2050 vs. 1990: as provided in the scenario description or calculated based on information provided in the study

Where the respective studies include indirect emissions, we have deducted these to obtain comparable results across studies. These deductions were done based on the method and assumptions stated in detail in section 4.1 (see Appendix 2).

in detail in section 4.1 (see Appendix 2).

Key assumptions:

1. Rationale behind GHG reduction: scenario may be driven by prices and economic considerations or by technical limitations excluding economic considerations
2. Technology: indicates level of innovativeness of included technologies (standard, standard with CCS, breakthrough with/without CCS)

Table 1: Summary table – scenario overview

Scenarios		**Scope**					**Results**				**Key assumptions**	
Reference	**Scenario-ID**	**GHG coverage**	**GEO**	**Base Year**	**Coverage of relevant NIR emissions**	**Direct* GHG emissions in 1990 (Mt CO_2eq.)**	**Direct* GHG emissions in 2030 (Mt CO_2)**	**Direct* GHG emissions in 2050 (Mt CO_2)**	**GHG reduction in 2030 vs. 1990**	**GHG reduction in 2050 vs. 1990**	**Rationale behind GHG reduction**	**Technology**
Entire industry sector												
UBA (2014)	THGND	All GHGs included	DE	1990	100%	n.a.	n.a.	14	n.a.	n.a.	Technical limits	Breakthrough without CCS
BMUB (2015)	CS 80	All GHGs included	DE	1990	100%	272	121	70	56%	74%	Policies and Measures	Standard
BMUB (2015)	CS 95	All GHGs included	DE	1990	100%	272	97	1	64%	100%	Technical limits	Standard with CCS
COM (2011)	Reference - fragm. action, ref fossil fuel prices	CO_2 only	EU27	1990	83%	1111	744	733	33%	34%	Economics	Standard
COM (2011)	Effect. Techn. + lower EII** effort - frag. action, ref. fossil fuel prices	CO_2 only	EU27	1990	83%	1111	74 4	511	33%	54%	Economics	Standard with CCS

Scenarios		**Scope**					**Results**				**Key assumptions**	
Reference	**Scenario-ID**	**GHG coverage**	**GEO**	**Base Year**	**Coverage of relevant NIR emissions**	**Direct* GHG emissions in 1990 (Mt CO_2eq.)**	**Direct* GHG emissions in 2030 (Mt CO_2)**	**Direct* GHG emissions in 2050 (Mt CO_2)**	**GHG reduction in 2030 vs. 1990**	**GHG reduction in 2050 vs. 1990**	**Rationale behind GHG reduction**	**Technology**
COM (2011)	Effect. Techn. - global action, low fossil fuel prices	CO_2 only	EU27	1990	83%	1111	722	178	35%	84%	Economics	Standard with CCS
COM (2011)	Effect. Techn. – fragm. action, ref. fossil fuel prices	CO_2 only	EU27	1990	83%	1111	711	178	36%	84%	Economics	Standard with CCS
COM (2011)	Delay. Clim. Act. - glob. action, low fossil fuel prices	CO_2 only	EU27	1990	83%	1111	767	133	31%	88%	Economics	Standard with CCS
COM (2011)	EII**: Effect. Techn. + lower EII effort - fragm. action, ref. fossil fuel prices	CO_2 only	EU27	1990	92%	880	607	431	31%	51%	Economics	Standard - with CCS
COM (2011)	EII**: Effect. Techn.- fragm. action, ref. fossil f. prices	CO_2 only	EU27	1990	92%	880	581	114	34%	87%	Economics	Standard with CCS

Scenarios		**Scope**					**Results**				**Key assumptions**	
Reference	**Scenario-ID**	**GHG coverage**	**GEO**	**Base Year**	**Coverage of relevant NIR emissions**	**Direct* GHG emissions in 1990 (Mt CO_2eq.)**	**Direct* GHG emissions in 2030 (Mt CO_2)**	**Direct* GHG emissions in 2050 (Mt CO_2)**	**GHG reduction in 2030 vs. 1990**	**GHG reduction in 2050 vs. 1990**	**Rationale behind GHG reduction**	**Technology**
ISI (2012)	No scenario	CO_2 only	EU27	2010 (adjusted to 1990 based on PRIMES)	58%	781	616	233	21%	70%	Economics	Standard
ISI (2014)	Potential 2030 HPI, 40% GHG reduction target	CO_2 only	EU27	1990 (from PRIMES)	58%	781	447	n.a	43%	n.a	Economics	Standard
ISI (2014)	Potential 2030 HPI 100% economic potential, 35% RES, 43% thermal eff.	CO_2 only	EU27	1990 (from PRIMES)	58%	781	355	n.a	55%	n.a	Economics	Standard
Iron and steel												
UBA (2014)	THGND	All GHGs included	DE	2010	100%	n.a.	n.a.	0	n.a.	99.7% to 2010	Technical limits	Breakthrough without CCS
BMUB (2015)	CS 95	All GHGs included	DE	1990	39%***	23***	11	0	52% (of process emissions)	98% (of process emissions)	Technical limits	Standard with CCS

Scenarios		**Scope**					**Results**				**Key assumptions**	
Reference	**Scenario-ID**	**GHG coverage**	**GEO**	**Base Year**	**Coverage of relevant NIR emissions**	**Direct* GHG emissions in 1990 (Mt CO_2eq.)**	**Direct* GHG emissions in 2030 (Mt CO_2)**	**Direct* GHG emissions in 2050 (Mt CO_2)**	**GHG reduction in 2030 vs. 1990**	**GHG reduction in 2050 vs. 1990**	**Rationale behind GHG reduction**	**Technology**
Van Ruijven et al. (2016)	Baseline	CO_2 only	Global	2010	n.a	n.a	n.a	1600	n.a	n.a	Economics	Standard
Van Ruijven et al. (2016)	20$ / tCO_2	CO_2 only	Global	2010	n.a	n.a	n.a	750	n.a	n.a	Economics	Standard without CCS
Van Ruijven et al. (2016)	100$ / tCO_2	CO_2 only	Global	2010	n.a	n.a	n.a	500	n.a	n.a	Economics	Standard without CCS
Van Ruijven et al. (2016)	100$ / tCO_2 - with CCS	CO_2 only	Global	2010	n.a	n.a	n.a	200	n.a	n.a	Economics	Standard with CCS
Wyns and Axelson (2016)	No scenario	CO_2, CH_4, N_2O	EU28	1990	100%	272	n.a	54	n.a	80%	Technical limits	Breakthrough without CCS
DECC (2015)	BAU	CO_2 only	UK	2013	n.a.	n.a.	n.a.	20	n.a.	n.a.	Economics	Standard
DECC (2015)	Max. Technology	CO_2 only	UK	2013	n.a.	n.a.	n.a.	9	n.a.	n.a.	Technical limits	Breakthrough with CCS
JRC (2012)	Baseline Scenario	CO_2 only	EU27	2009	129%	352	160	n.a	55%	n.a	Economics	Standard with CCS

Scenarios		**Scope**					**Results**				**Key assumptions**	
Reference	**Scenario-ID**	**GHG coverage**	**GEO**	**Base Year**	**Coverage of relevant NIR emissions**	**Direct* GHG emissions in 1990 (Mt CO_2eq.)**	**Direct* GHG emissions in 2030 (Mt CO_2)**	**Direct* GHG emissions in 2050 (Mt CO_2)**	**GHG reduction in 2030 vs. 1990**	**GHG reduction in 2050 vs. 1990**	**Rationale behind GHG reduction**	**Technology**
JRC (2012)	Alternative Scenario 2 (200€-CO_2)	CO_2 only	EU27	2009	129%	352	149	n.a	58%	n.a	Economics	Breakthrough with CCS
BCG (2013)	Baseline Upper Boundary	CO_2 only	EU27	1990	98%	266	n.a	270	n.a	-2%	Technical limits	Standard
BCG (2013)	Continued improved efficiency Upper Boundary	CO_2 only	EU27	1990	98%	266	n.a	246	n.a	8%	Economics	Standard
BCG (2013)	Lower theoretical boundary without CCUS	CO_2 only	EU27	1990	98%	266	n.a	165	n.a	38%	Technical limits	Breakthrough without CCS
BCG (2013)	Lower theoretical boundary with CCUS	CO_2 only	EU27	1990	98%	266	n.a	113	n.a	58%	Technical limits	Breakthrough with CCS

Scenarios		**Scope**					**Results**				**Key assumptions**	
Reference	**Scenario-ID**	**GHG coverage**	**GEO**	**Base Year**	**Coverage of relevant NIR emissions**	**Direct* GHG emissions in 1990 (Mt CO_2eq.)**	**Direct* GHG emissions in 2030 (Mt CO_2)**	**Direct* GHG emissions in 2050 (Mt CO_2)**	**GHG reduction in 2030 vs. 1990**	**GHG reduction in 2050 vs. 1990**	**Rationale behind GHG reduction**	**Technology**
EUROFER (2013)	As in BCG (2013)	CO_2 only	EU27	1990	see BCG	see BCG	see BCG	see BCG	see BCG	see BCG	see BCG	see BCG
Pulp and Paper												
UBA (2014)	THGND	All GHGs included	DE	2010	100%	12,19	n.a.	0	n.a.	100%	Technical limits	Breakthrough without CCS
DECC (2015)	BAU	CO_2 only	UK	2012	n.a.	n.a.	n.a.	2	n.a.	n.a.	Economics	Standard
DECC (2015)	Max technology clustering and electrification	CO_2 only	UK	2012	n.a.	n.a.	n.a.	0	n.a.	n.a.	Technical limits	Breakthrough
DECC (2015)	Max. technology biomass	CO_2 only	UK	2012	n.a.	n.a.	n.a.	0	n.a.	n.a.	Technical limits	Breakthrough with biomass
CEPI (2011)	No scenario	CO_2 only	EU27	1990	115%	40	31	24	24%	40%	Technical limits	without CCS
CEPI (2011)	No scenario	CO_2 only	EU27	1990	115%	40	31	10	24%	75%	Technical limits	Breakthrough
Chemicals												
UBA (2014)	THGND	All GHGs included	DE	2010	100%	n.a.	n.a.	0,5	n.a.	99%	Technical limits	Breakthrough without CCS

Scenarios		**Scope**					**Results**				**Key assumptions**	
Reference	**Scenario-ID**	**GHG coverage**	**GEO**	**Base Year**	**Coverage of relevant NIR emissions**	**Direct* GHG emissions in 1990 (Mt CO_2eq.)**	**Direct* GHG emissions in 2030 (Mt CO_2)**	**Direct* GHG emissions in 2050 (Mt CO_2)**	**GHG reduction in 2030 vs. 1990**	**GHG reduction in 2050 vs. 1990**	**Rationale behind GHG reduction**	**Technology**
BMUB (2015)	CS 95	All GHGs included	DE	2010	100%	30	11	1	63%	98%	Technical limits	Standard with CCS
DECC (2015)	BAU	CO_2 only	UK	2012	n.a.	n.a.	n.a.	13	n.a.	n.a.	Economics	Standard
DECC (2015)	Max. Technology	CO_2 only	UK	2012	n.a.	n.a.	n.a.	4	n.a.	n.a.	Technical limits	Breakthrough without CCS
DECC (2015)	Max. Technology with biomass	CO_2 only	UK	2012	n.a.	n.a.	n.a.	3,3	n.a.	n.a.	Technical limits	Breakthrough with CCS
Wyns and Axelson (2016)	No scenario	All GHG included	EU28	1990	100%	325	n.a	585	n.a	80%	Technical limits	Breakthrough without CCS
CEFIC (2013)	Continued Fragmentation	CO_2, N_2O, PFCs, HFCs	EU27	1990	100%	324	n.a	223	n.a	31%	Economics	Standard
CEFIC (2013)	Differentiated Global Action	CO_2, N_2O, PFCs, HFCs	EU27	1990	100%	324	n.a	94	n.a	71%	Economics	Standard with CCS

Scenarios		**Scope**					**Results**				**Key assumptions**	
Reference	**Scenario-ID**	**GHG coverage**	**GEO**	**Base Year**	**Coverage of relevant NIR emissions**	**Direct* GHG emissions in 1990 (Mt CO_2eq.)**	**Direct* GHG emissions in 2030 (Mt CO_2)**	**Direct* GHG emissions in 2050 (Mt CO_2)**	**GHG reduction in 2030 vs. 1990**	**GHG reduction in 2050 vs. 1990**	**Rationale behind GHG reduction**	**Technology**
Non-metallic minerals: Cement												
BMUB (2015)	CS 95	All GHGs included	DE	1990	45%***	15	8	0	47% (of process emissions)	100% (of process emissions)	Technical limits	Standard with CCS
Van Ruijven et al. (2016)	Baseline	CO_2 only	Global	2010	n.a	n.a	n.a	2750	n.a	n.a	Economics	Standard
Van Ruijven et al. (2016)	20$ / tCO_2	CO_2 only	Global	2010	n.a	n.a	n.a	2000	n.a	n.a	Economics	Standard
Van Ruijven et al. (2016)	100$ / tCO_2 - with CCS	CO_2 only	Global	2010	n.a	n.a	n.a	500	n.a	n.a	Economics	Standard with CCS
Wyns & Axelson (2016)	No scenario	CO_2 only	EU28	1990	n.a	164	n.a	295	n.a	80%	Technical limits	Breakthrough with CCS
CEMBUREAU (2013)	Max abatement without breakthrough technologies	CO_2 only	EU27	1990	n.a	157	n.a	112	n.a	29%	Technical limits	Standard
CEMBUREAU (2013)	Max abatement with	CO_2 only	EU27	1990	n.a.	157	n.a	33	n.a	79%	Technical limits	Breakthrough with CCS

Scenarios		**Scope**					**Results**				**Key assumptions**	
Reference	**Scenario-ID**	**GHG coverage**	**GEO**	**Base Year**	**Coverage of relevant NIR emissions**	**Direct* GHG emissions in 1990 (Mt CO_2eq.)**	**Direct* GHG emissions in 2030 (Mt CO_2)**	**Direct* GHG emissions in 2050 (Mt CO_2)**	**GHG reduction in 2030 vs. 1990**	**GHG reduction in 2050 vs. 1990**	**Rationale behind GHG reduction**	**Technology**
	breakthrough technologies											
UBA (2014)	THGND	All GHGs included	DE	2010	100%	24	n.a.	6	n.a.	74%	Technical limits	Breakthrough without CCS
DECC (2015)	BAU	CO_2 only	UK	2012	n.a.	n.a.	n.a.	7	n.a.	n.a.	Economics	Standard
DECC (2015)	Max. technology without CCS	CO_2 only	UK	2012	n.a.	n.a.	n.a.	5	n.a.	n.a.	Technical limits	Breakthrough without CCS
DECC (2015)	Max. technology with CCS	CO_2 only	UK	2012	n.a.	n.a.	n.a.	3	n.a.	n.a.	Technical limits	Breakthrough with CCS
IEA (2009)	Baseline with high demand	CO_2 only	Global	2006	n.a	n.a	n.a	2796	n.a	n.a	Technical limits	Standard
IEA (2009)	Roadmap with high demand	CO_2 only	Global	2006	n.a	n.a	n.a	2521	n.a	n.a	Technical limits	Standard
IEA (2009)	Roadmap with high demand with CCS	CO_2 only	Global	2006	n.a	n.a	n.a	1548	n.a	n.a	Technical limits	Standard with CCS

Scenarios		**Scope**					**Results**				**Key assumptions**	
Reference	**Scenario-ID**	**GHG coverage**	**GEO**	**Base Year**	**Coverage of relevant NIR emissions**	**Direct* GHG emissions in 1990 (Mt CO_2eq.)**	**Direct* GHG emissions in 2030 (Mt CO_2)**	**Direct* GHG emissions in 2050 (Mt CO_2)**	**GHG reduction in 2030 vs. 1990**	**GHG reduction in 2050 vs. 1990**	**Rationale behind GHG reduction**	**Technology**
Non-metallic minerals: Ceramics												
Ceramie-Unie (2013)	Scenario without electrification of kilns	CO_2 only	EU27	1990	n.a	22	15,5	9	30%	59%	Technical limits	Breakthrough with CCS
Ceramie-Unie (2013)	Scenario with electrification of kilns	CO_2 only	EU27	1990	n.a	22	15,5	5	30%	77%	Technical limits	Breakthrough with CCS
DECC (2015)	BAU	CO_2 only	UK	2012	n.a.	n.a.	n.a.	1	n.a.	n.a.	Economics	Standard
DECC (2015)	Max. Technology	CO_2 only	UK	2012	n.a.	n.a.	n.a.	1	n.a.	n.a.	Technical limits	Breakthrough with CCS
Non-metallic minerals: Lime												
UBA (2014)	THGND	All GHGs included	DE	2010	100%	9	n.a.	4	n.a.	61%	Technical limits	Breakthrough without CCS
ECOFYS (2014)	No scenario	CO_2 only	EU28	2010	n.a	n.a	23	18	n.a	n.a	Technical limits	Standard
Non-ferrous metals: Aluminium												
UBA (2014)	THGND	All GHGs included	DE	2010	100%	14,6	n.a.	0	n.a.	100%	Technical limits	Breakthrough without CCS

Scenarios		**Scope**					**Results**				**Key assumptions**	
Reference	**Scenario-ID**	**GHG coverage**	**GEO**	**Base Year**	**Coverage of relevant NIR emissions**	**Direct* GHG emissions in 1990 (Mt CO_2eq.)**	**Direct* GHG emissions in 2030 (Mt CO_2)**	**Direct* GHG emissions in 2050 (Mt CO_2)**	**GHG reduction in 2030 vs. 1990**	**GHG reduction in 2050 vs. 1990**	**Rationale behind GHG reduction**	**Technology**
BMUB (2015)	CS 95	All GHGs included	DE	1990	42%***	1***	0	0	57% (of process emissions)	66% (of process emissions)	Technical limits	Standard with CCS
EAA (2012)	No scenario	CO2, PFCs	EU27	1990	n.a	32	16	22	52%	31%	Technical limits	Breakthrough

*Where the respective studies include indirect emissions, we have deducted these to obtain comparable results across studies. These deductions were done based on the method and assumptions stated in detail in section 4.1 (see Appendix 2).

**EII: Energy Intensive Industry

***Numbers in brackets indicate the emissions reported under total industrial processes (i.e., only process-related emissions). These numbers are discussed individually in the study BMUB (2015). The mitigation potential for energy-related emissions is analysed as well in BMUB 2015 but is reported on an aggregate level, i.e. not differentiated by industry sector. The results part of Table 1 for the indiviual industry sectors therefore only relates to emissions reported under total industrial processes.

3 Appendix 1: Study profiles

3.1 Studies for the whole industrial sector

3.1.1 COM 2011 Low-carbon roadmap and impact assessment

European Commission 2011, Impact assessment: A Roadmap for moving to a competitive low carbon economy in 2050, 134 pages

Table 2: COM 2011 Low-carbon roadmap and impact assessment general information

Carried out by:	modelling: IIASA, E3M-Lab, JRC elaborated by DG CLIMA in collaboration with DG ENER and DG MOVE
Commissioned by:	European Commission
Link:	Roadmap: http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52011DC0112%20 Impact assessment: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52011SC0288&from=EN
Range of emission reductions achieved	-33% to -88% (2050 vs. 1990)
Aim:	The roadmap presents possible ways up to 2050 that could enable the EU to deliver the targeted emission reductions of -80% to -95% compared to annual emissions in 1990.The impact assessment contains the background analysis for the published roadmap. While the roadmap only includes one scenario to reach the targeted 80% reduction, the impact assessment compares different decarbonisation scenarios to provide insights on how EU policy should develop to enable deep emission reductions, sustainable growth and at the same time addresses energy security.
Sectoral coverage:	Power, transport, industry (iron & steel, non-ferrous metals, chemical, non-metallic minerals, pulp & paper), residential and service sectors, agriculture and non-CO_2 emissions, LULUCF. For the five industrial sub-sectors (iron & steel, non-ferrous metals, chemical, non-metallic minerals, paper & pulp) CO_2 emissions are detailed. Non-CO_2 emissions are only published in an aggregated way and not detailed, neither for industrial subsectors nor for the aggregate industrial sector.
Geography:	EU27
Time horizon:	1990-2050
Modelling approach:	A joint analytical framework has been elaborated between the three DGs MOVE, ENER and CLIMA. Modelling is based on the energy system models POLES and PRIMES complemented by GAINS to assess non-CO_2 emissions from agriculture and industry with input from the agricultural model CAPRI, and G4M and GLOBIOM to assess effects of LULUCF. GEM E3 was used to model the impacts on GDP, overall employment and competitiveness for energy intensive industries. For the impact assessment, three scenarios (global baseline, global action and fragmented action) were modelled with POLES to reflect the interaction of climate action on a global level and fossil fuel prices. The resulting information on impacts of climate action on fossil fuels prices is used to determine the fossil fuel prices assumed for the scenarios modelling EU climate action. Carbon prices are the driver for reductions in the scenarios, assuming an equal carbon price across all sectors and gases.

General assumptions:	It is assumed that GDP increases with declining growth rates over time and great variation among Member States. EU-27 GDP is expected to rise by 1.7% p.a. from 2010 to 2050, in total. This is composed from a rise of 2.0% p.a. up to 2030 and only 1.5% p.a. after 2030. The five industrial sectors mentioned above are projected to continue to grow in the reference and decarbonisation scenarios, at slightly lower rates than other industrial sectors. CCS penetration is determined economically, depending on CO_2-prices. CCS technology develops in every country without regulatory acceptance problems. Storage capacity for CO_2 within Europe is 250,000 Mt CO_2.
Other aspects	The focus of the roadmap and impact assessment is the EU. The global context was considered in the sense that climate action interacts at the global level and the effects e.g. on fossil fuel prices depend on the action of other players beyond the EU.

3.1.1.1 Scenario descriptions and main assumptions

The three main scenarios of the study – a baseline scenario, a decarbonisation scenario with global action and a decarbonisation with fragmented action – are divided into sub-scenarios for further analysis. The following paragraphs present a description and the specific assumptions of the different scenarios.

1. **The Reference scenario** aims to project emissions up to 2050 based on already implemented EU and national policies. It assumes:
    a. The EU Emission Trading System will be amended as planned with a cap decreasing linearly by the adopted linear reduction factor after 2020, resulting in a cap of nearly -70% below 2005 emission levels by 2050. The ETS carbon price is expected to rise to 16.5 €/t CO_2eq. in 2020 and 50 €/t CO_2eq. in 2050.
    b. A full implementation of Non-ETS and renewable energy legislations is assumed from 2020 but no detailed assumptions are presented. A uniform Non-ETS carbon value of 5 €/t CO_2eq. across the EU is used.
    c. A substantial decline in subsidies towards renewable energies is assumed with rates differentiated by technology. The start value of subsidies is on average 50 €/MWh for RES and 55 €/MWh for bio fuel decreasing to 35 €/MWh from 2020 onwards.
    d. National nuclear policies are assumed to continue with the status of mid-2010.
2. **The Decarbonisation scenarios in the context of Global Climate Action assume global** action leading to a reduction of global emissions of -50% by 2050 compared to 1990 while the EU pursues a goal of -80%. The Global Climate Action scenarios are the only scenarios in which global primary energy demand is decreasing (after 2030), all other scenarios assume an increasing global energy demand. The scenario considers common global carbon prices and international energy and fossil fuel prices as main drivers for emission development. The following paragraphs describe the subscenarios and their assumptions.
    a. In the **Effective and widely accepted technology** scenario all major carbon reduction technologies are assumed to be enabled by policies. This refers to:
        i) Extended share of renewable technologies
        ii) Higher energy intensity improvements driven by high carbon values.
        iii) Commercial use of CCS starting in 2020
        iv) Implementation of nuclear policies in the countries where new nuclear plants are accepted
        v) Electrification of transport enabled via a fourfold decrease of cost of batteries in electric cars batteries.
    b. The subscenario **Delayed CCS** assumes a delay of 10 to 15 years in the deployment of CCS due to problems with commercialization of storage and transportation of CO2 e.g. because of public acceptance problems.

   c. The subscenario **Delayed electrification** considers a delay of 10 to 15 years in the electrification of transportation due to slower decrease in battery cost, delay in R&D and slower development of mass production for electric vehicles.
   d. The subscenario **Delayed climate action** assumes that no climate action is taken between 2020-2030 and the CO_2 prices will be the same as in the reference scenario after successful implementation of the 2020 package. However the CO_2 price increase after 2030 is assumed to be on a level that would equalize the cumulative emission reductions over the period of 2010-2050 in the "Effective and widely accepted technology" scenario. The delay is assumed to be associated with higher cost for technological change for the electrification of transportation because development and deployment take place later compared to the "Effective and widely accepted technology" scenario. For other technologies cost are assumed to be unchanged.
3. **The Decarbonisation scenarios** in the context of **Fragmented Climate Action** explore the possible outcome if the world did not act in line with the 2°C target, but if the EU still maintains its policies for climate action.
   a. The subscenario **Effective and widely accepted technology in EU** assumes that the EU pursues the actions to reach an emission reduction of -80% while the rest of the world doesn't act for climate protection similarly. This means fossil fuel prices remain as in the reference scenario while the other assumptions are equal to those in the global action scenario "Effective and widely accepted technology".
   Two options concerning the treatment of industry are explored
      i) No Special treatment for EII (Energy Intensive Industry): The same reduction target as in the global action effective technology scenario is pursued. This lays the basis for investigating the impact for industry: i.e. the investment costs they would experience, type and extend of necessary R&D support or required level of direct support to compensate the industry for those additional costs that they bear compared to companies in third countries.
      ii) Lower EII Effort: Special provisions are given to energy intensive industries which are exposed to global competition to have carbon prices as in the reference scenario which eventually leads to less emission reduction.
      iii) The subscenario **Delayed EU climate action in a world of fragmented climate action** has the same energy prices as the reference scenario. The other assumptions are the same as in the subscenario "delayed climate action" in the global climate action scenario.
4. Further **Common scenarios** explore the effect of an oil shock or high fossil fuel prices in all main scenarios:
   a. **Oil shock**: the scenario assesses the impact of doubled oil prices in 2030. Coal and gas prices also increase, but the increase is less severe. After 2030 the oil prices in the scenario gradually decrease.
   b. **High fossil fuel prices**: considers a doubling of fossil fuel prices in 2030 which than remain stable until 2050.

The following tables summarize the main assumptions on CO_2 prices, oil prices and primary energy demand.

Table 3: COM 2011 scenario assumptions for primary energy demand, oil price, CO_2 price

		Indicator	2010	2020	2030	2050
Reference		EU 27 primary energy demand (index: 1990 = 100)	104	105	107	107
		oil-price ($'05 / Barrel)	70	78	96	138

		Indicator	2010	2020	2030	2050
		CO2-price (€ /t CO2)		16.5	36	50
Global action	all subscenarios	EU27 primary energy demand (index: 1990 = 100)	104	105	100	90
		oil-price ($’05 / Barrel)	70	74	77	69
	Effective technology	CO2-price (€ /t CO2)		25	60	190
	Delayed CCS	CO2-price (€ /t CO2)		25	62	370
	Delayed electrification	CO2-price (€ /t CO2)		25	57	245
Fragmented action	All subscenarios	EU27 primary energy demand (index: 1990 = 100)	104	104	99	89
		oil-price ($’05 / Barrel)	70	75	88	117
	Effective technology	CO2-price (€ /t CO2)		25	51	147
	Oil shock	CO2-price (€ /t CO2)		25	45	117
	High fossil fuel prices	CO2-price (€ /t CO2)		25	42	104
	Delayed EU climate action	CO2-price (€ /t CO2)		16.5	36	250

3.1.1.2 Overview of scenario results

The below table presents the results from the different scenarios from the low carbon roadmap’s impact assessment which are particularly affecting the industrial sector. Since non-CO_2 gases are assumed to be reduced to negligible amounts due to cheap abatement options they are not considered in the industry analysis.

Table 4: COM 2011 Overview of scenario results for the energy intensive industries

Scenario	Emission levels (2050)	Assumptions	Production & Implemented Technologies
Reference Reference fossil fuel prices	-33% decrease from 1990 levels	No global action Fragmented action by the EU Reference fossil fuel price increase	Continuing trend in technological improvements No new technology
Global Action Effective technology	-88% decrease from 1990 levels	Global action Low fossil fuel price increase High carbon price globally	All effective technologies are implemented including CCS Energy Intensity Increases contribute nearly 75% reduction in 2050 compared to 1990 CCS is applied for remaining energy intensive industrial CO_2 emissions from 2035 (p.72 impact assessment)

Scenario	Emission levels (2050)	Assumptions	Production & Implemented Technologies
Global Action Delayed CCS	-87% decrease from 1990 levels	Global action Low fossil fuel price increase High carbon price globally	All effective technologies are implemented CCS commercialization is delayed by 10-15 years
Fragmented Action – No special treatment for EII	-87% decrease from 1990 levels	No global action High ambition in EU industry to reduce emissions Reference fossil fuel price increase	All effective technologies are implemented including CCS Production decrease with -2.7% to -4.3% compared to reference by 2030 (see table 7 on p. 45 of the impact assessment)
Fragmented Action – Low EII effort	-51% decrease from 1990 levels	No global action EU EII is subject to lower reduction targets Reference fossil fuel price increase	Limited technological advancement in industry No CCS n.a.

3.1.1.3 Technology overview

No specific technologies except for CCS and electrification of transport are explicitly addressed in the study.

3.1.2 Fraunhofer ISI 2012 Energy Efficiency for Climate Protection

Fraunhofer ISI 2012, Concrete Paths of the European Union to the 2°C Scenario: Achieving the Climate Protection Targets of the EU by 2050 through Structural Change, Energy Savings and Energy Efficiency Technologies, 266 pages

Table 5: Fraunhofer ISI 2012 Energy efficiency for climate protection, general information

Carried out by:	Fraunhofer Institute for Systems and Innovation Research ISI
Commissioned by	German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU)
Link:	https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cce/2012/BMU_Policy_Paper_20121022.pdf
Range of emission reductions achieved	-70% (2050 vs. 1990)
Aim:	The study is analysing in depth the potentials and contributions of energy efficiency and energy saving options to the climate policy targets in the EU up to 2050.
Sectoral coverage:	Total coverage: Households & tertiary, industry, transport Detailed analysis and factsheets for: Pulp and paper, cross-cutting technologies: e-drive optimization, steam and hot water generation, electric drives. Aggregated coverage for the remaining industry (Chemicals, non-ferrous metals, iron and steel, glass, cement, refineries). Detailed Households & tertiary coverage: Building envelope, heating and cooling systems, lighting, green ICT, household appliances Detailed Transport coverage: technical improvements, behavioural changes, e-mobility

	The estimated potentials for industrial sectors include reductions in the conversion sector, but these are shown separately.
Geography:	EU27
Time horizon:	2008 (EU baseline scenario) - 2050
Modelling approach:	The study is based on two previous studies: The European-wide study on energy efficiency potentials up to the year 2030 (ISI 2009a) and the ADAM report for the time horizon between 2030 and 2050 (ISI 2009b) and does not contain original modelling work. Energy efficiency and energy savings potentials at the demand side in ISI 2009a (the ESD potential study) were estimated based on the bottom-up MURE simulation tool supported by the Green-X model to determine potentials for decentralized renewables. The potentials are estimated in several scenarios based on (usual) reinvestment cycles , the competition between more or less energy efficient savings options over time (dynamics in technology diffusion) and learning and scale effects which lead to a cost decrease of energy efficient technologies over time (dynamics in technology innovation). Emission reductions are calculated based on primary energy demand in the baseline scenarios and the savings of the energy efficiency measures by the use of emission factors. The emission reduction potentials are presented in relation to a baseline of 2050 emissions.
Assumptions:	Fossil fuel prices and macroeconomic drivers are taken from the POLES 2007 baseline for the original ISI 2009a study and adjusted to the newer POLES 2009 baseline. Savings potentials are differentiated into high hanging fruits and low hanging fruits, which are modelled via different discount rates to reflect the relative risk and other barriers to the investments decision. For low hanging fruits a higher discount rate of 30% in industry is assumed which implies that potentials are realized that still have relatively high risk. High hanging fruits will only be realised if financial and non-financial barriers to the energy efficiency investment are removed. This is modelled with a lower discount rate of 8% (for comparison: the discount rate in PRIMES is 12%).
Other aspects	The estimations are compared to the BAU estimates from the EU Commission study: EU energy trends to 2030 - Update 2009. Calculations are only presented with relation to the year 2010. It is not directly without problems possible to derive reduction potentials compared to 1990 since in contrast to the PRIMES data the indirect emissions have been included.

3.1.2.1 Scenario descriptions and main assumptions

The study differentiates the potentials into three categories:

- **"Low-hanging fruits (LHF)":** Potentials that are already economically feasible under high discount rates reflecting high risk perception.
- **"High-hanging fruits (HHF)":** Potentials which are economic at low discount rates which reflects that economic and non-economic barriers to investment have been removed by different policy instruments.
- **"Immature fruits (IF)":** Potentials that are close to being economic under low discount rates and may be realised under acceptable additional costs.

Fossil fuel prices and macroeconomic drivers are taken from the POLES baseline 2007 for the original ISI 2009a study and adjusted to the newer POLES 2009 baseline.

3.1.2.2 Technology Overview

The study details technologies only for selected sectors. Within industry, the pulp and paper sector is presented in more detail. The technologies covered are:

- Mechanical pulp - Recovery of waste heat (Commercial)
- Mechanical pulp - Water free paper production (R&D)

- Chemical pulp - Gasification of black liquor (Demo)
- Recovered paper - efficient de-inking, and efficient screening or high-consistency pulping (Commercial)
- Pulp refining - chemical modification of fibres (Demo)
- Pulp refining - waste heat and heat integration

Furthermore, the study considers in detail the potential for industrial steam and hot water generation as thermal cross-cutting technology. This field covers efficient industrial space heating and further diffusion of combined heat and power generation (CHP) as well as efficiency improvements in heat and power generation. The study covers energy efficiency improvements in different boiler concepts (fire-tube boiler, water tube boilers, high-speed steam generators and thermal oil heaters) as well as alternative generation concepts.

- CHP (Commercial/emerging commercial)
- solid oxide fuel cells (R&D, Demo)
- economizers that work similarly to heat exchangers and recover heat from flue gases, condensing heating technology (Commercial)
- optimized O_2-regulation in burners (R&D, Commercial)
- continuously variable burners (Demo, Commercial)
- improved boiler insulation (R&D, Commercial)

Additionally, electric drives and e-drive optimization have been considered as cross-cutting technologies in the field of electricity. Since this relates to indirect emissions, we do not describe this aspect in more detail.

3.1.2.3 Overview of results

The reductions in CO_2 emissions are not detailed for the different groups of potentials.

Overall emission reduction in the industry sector is estimated at 377 Mt CO_2. compared to a baseline of 767 Mt CO_2 eq. This implies remaining emissions of 390 Mt CO_2eq. in 2050 for the industrial sector. Additional savings in the conversion sector would further reduce emissions to 233 Mt CO_2.

3.1.3 Fraunhofer ISI 2014 Energy efficiency/saving potentials until 2020 and beyond

Fraunhofer ISI 2014, Study evaluating the current energy efficiency policy framework in the EU and providing orientation on policy options for realising the cost-effective energy efficiency/saving potential until 2020 and beyond, 204 pages

Table 6: Fraunhofer ISI 2014 Energy efficiency/saving potentials, general information

Carried out by:	Fraunhofer Institute for Systems and Innovation Research ISI,TU Wien and PriceWaterhouseCoopers
Commissioned by	DG Ener
Link:	https://ec.europa.eu/energy/sites/ener/files/documents/2014_report_2020-2030_eu_policy_framework.pdf
Range of emission reductions achieved	-43% to -55% (2030 vs. 1990)
Aim:	The study is analysing in depth the potentials and contributions of energy efficiency and energy saving options to the climate policy targets in the EU up to 2030 based on bottom-up modelling of the effect of policies.

Sectoral coverage:	buildings, transport, residential, industry (results for eight sub-sectors: Chemical industry, Engineering and other metal, Food, drink and tobacco, Iron and steel, Non-ferrous metals, Non-metallic mineral products, Other non-classified, Paper and printing)
Geography:	EU27
Time horizon:	2020, 2030
Modelling approach:	The study relies on bottom-up modelling of final energy demand by sectors and the effect of policies on the final energy demand. For the different sectors, the study applies the following models: buildings: INVERT/EE-Lab model (run by TU Wien) industry: FORECAST platform (run by Fraunhofer ISI) electricity uses in the residential and service sector. FORECAST platform (run by Fraunhofer ISI) transport: ASTRA model (run by Fraunhofer ISI) power sector and efficiency options: PowerACE model (run by Fraunhofer ISI) Energy savings from the measures were estimated for 2020. Furthermore energy-efficiency potentials up to 2030 were estimated.
Assumptions:	The study is based on data from PRIMES 2009 but updated with the drivers in PRIMES 2012. For the industrial sector the main drivers of energy demand are gross value added (PRIMES 2013) and employment (EUROSTAT) as well as physical production per process (PRODCOM and various sources, estimation coupled to gross value added). For the energy savings, the study draws on a database of national energy efficiency measures with quantitative impacts in energy terms from 2008 onwards.

3.1.3.1 Scenario descriptions and main assumptions

The study analyses a baseline and six scenarios:

Baseline No early action

- The baseline without early action includes only measures before 2008 and is said to be roughly comparable with the reference development of PRIMES 2009 (corrected for the drivers from PRIMES 2013),even though PRIMES includes measures up to early 2009.

Baseline incl. early action

- The baseline with early action includes measures up to 2013 and is said to be comparable with PRIMES 2013.
- Energy taxes are assumed to remain at the level of 2013.

Baseline with measures

- In addition to that, the baseline with measures includes also measures which are accepted or close to acceptance in 2014 and the near future.

Additional measures

- The baseline with additional measures extends the impact of existing measures for each sector by around 3% in order to reach the EED target in case there is a gap. The scenario also proposes and applies some new measures (representing a generalization of successful measures) especially for the transport sector and the space heating & hot water.

Potential 2030 (low policy intensity)

- The scenario “Potential_2030_LPI” assumes high discount rates and persistent barriers for energy efficiency. It is assumed that payback times of up to 2 years are accepted by 50% of companies in the industrial sector.

Potential 2030 (high policy intensity)

- The scenario “Potential_2030_HPI” assumes low discount rates and a partial or even total removal of barriers to energy efficiency. It is assumed that a payback time of up to 5 years is accepted by 60% of companies in the industrial sector.

Potential 2030 (near economic)

- The scenario “Potential_2030_NE” assumes that also those potentials will be realized, that are not yet economic (that is the Net Present Value is negative given the discount rates used in the HPI scenario) but that have cost only slightly above the current level. Companies in the industrial sector are assumed to accept interest rates close to zero and payback times above 5 years.
- The scenario assumes very ambitious boiler standards and a very dynamic upgrading of standards. Also, steam system improvement is very ambitious assuming that after 20 years all steam systems will be retrofitted or replaced to cope with BAT efficiency. However, the scenario does not assume a premature replacement of equipment.
- Additionally, the scenario assumes improved material efficiency strategies e.g. the reduction of the clinker share in cement production and replacement by alternative “fillers”, the shift from primary production to secondary (e.g. steel, aluminium and paper) and reduced product demand.

Table 7: Fuel prices and CO_2 prices in Fraunhofer ISI 2014

	Indicator	2010	2015	2020	2030	2050
	oil price	60	86	88.5	93.1	na
	gas price	37.9	53.8	61.5	64.5	na
	coal price	16	22	22.6	24	na
Baseline no early action	CO_2 price (€ /t CO_2)	na	5	10	10	na
Baseline early action	CO_2 price (€ /t CO_2)		10			
additional measures and low policy intensity	CO_2 price (€ /t CO_2)	na	10	10	35	n.a
high policy intensity and near economic	CO_2 price (€ /t CO_2)		15	25	50	

Source of fuel prices: PRIMES 2013

3.1.3.2 Overview of included measures/policies

The study investigates the impact of several energy efficiency measures in the different sectors. The report does not provide much detail on technologies but rather the policies driving the adoption and diffusion of energy efficiency technologies.

Within the industry sector, the following policies are modelled:

- The EU emissions trading scheme (ETS): modelled via the price of EU Allowances (EUAs). The model considers around 50 individual energy intensive processes and products with a differentiation of whether it is within the scope of the EU ETS or not (examples of products are: clinker, flat glass, container glass, primary and secondary aluminium, oxygen steel, electric steel, coke, sinter, paper, ceramics, ammonia, adipic acid, chlorine) differentiating phase 3 and before. The price of EUAs influences the cost-effectiveness of energy-efficiency measures and, consequently, investment decisions.
- Energy taxes: For the industrial sector 14 individual energy carriers are included in the model with country specific prices including taxes (electricity, light fuel oil, heavy fuel oil, natural gas, lignite, hard coal, district heating, biomass, etc.). Again, prices speed-up diffusion of energy-efficiency measures via increasing the cost-effectiveness.
- Minimum energy performance standards (MEPS) are implemented in the frame of the EU Ecodesign Directive that addresses products in the area of electric cross-cutting technologies, like lighting, ventilation or pump systems or thermal cross-cutting technologies like steam and hot water. Measures for which an Ecodesign Regulation sets MEPS experience a faster diffusion in the model.
- Building standards as well as heating systems in the industrial sector are included via a stock model approach. Standards are modelled straight forward by restricting the market shares of inefficient building insulation or boilers.
- Information-based and national policies summarizes a bundle of policy instruments aiming to overcome non-financial barriers to the adoption of energy-efficiency measures e.g. energy audits, labelling or energy management. This bundle of measures is modelled by adapting the payback time expectations of companies: when a country has a very comprehensive set of information-based policies, companies are expected to accept longer payback times. Thereby heterogeneous bundles of national policy measures are included in the analysis

3.1.3.3 Overview of scenario results

The following table presents the results for industrial sector CO_2 emissions for the additional measures scenario up to 2020 combined with the Potential 2030 scenario with high policy intensity and two different sets of assumptions. For the other scenarios the results are not detailed in the report with respect to greenhouse gas emissions.

The study indicates that in the HPI combined with higher penetration of renewables (35% RES share in final energy) and increased efficiency in the conversion sector, the total GHG emissions can be decreased by 49.5% in 2030 compared to 1990 based on the realization of economic potentials. The energy related CO_2-emissions are estimated to be potentially reduced by 55% in 2030 compared to 1990.

The study has a focus on energy and energy demand reduction. The potentials are only given for 2020 and 2030 but not for 2050 and not all numbers are specified for the industrial sector.

Table 8: Overview of scenario results from Fraunhofer ISI 2014

Scenario	Emission level [Mt CO_2] (2020)	Emission level [Mt CO_2] (2030)	Assumptions
Additional measures Potential 2030 HPI 27% RES	496	401	100% realization of economic potentials (HPI) 27% renewable (44% RES-E in gross electricity generation) 41% thermal power efficiency

Scenario	Emission level [Mt CO_2] (2020)	Emission level [Mt CO_2] (2030)	Assumptions
Additional measures Potential 2030 HPI 35% RES	496	355	100% realization of economic potentials (HPI) 35% renewable (47% RES-E in gross electricity generation) 43% thermal power efficiency, enhancement of decentral Combined Heat and Power Generation
Additional measures Potential 2030 HPI	496	447	assuming 40% GHG reduction to be achieved (EU27) in 2030 (48% realization of economic potentials) 27% renewables

3.1.4 UBA 2014 Germany in 2050 – a greenhouse gas-neutral country

UBA 2014 Germany in 2050 – a greenhouse gas-neutral country (Treibhausgasneutrales Deutschland im Jahr 2050), 348 pages

Table 9: UBA 2014 Germany in 2050 – a greenhouse gas-neutral country, general information

Carried out by:	German Environmental Agency, for parts Oeko-Institut and Thünen-Institut
Commissioned by:	German Environmental Agency
Link:	https://www.umweltbundesamt.de/themen/jetzt-auch-auf-englisch-studie
Range of emission reductions achieved	-95% (2050 vs. 1990)
Aim:	The study presents one possible scenario of a greenhouse gas-neutral society in Germany in 2050. It focuses on the description of a greenhouse gas-neutral German energy system and non-energetic emissions from agriculture, land-use, land-use change and forestry and waste and water in 2050. Descriptions of the pathway to reach this final state are not provided. Instead, the study focuses on the technical feasibility, i.e. the identification of key technologies and partly changes in consumption necessary to reach a greenhouse gas-neutral society. Also, costs for reaching the final state are not part of the investigation. A detailed description of the status quo (year 2010) is provided for comparison with the final state.
Sectoral coverage:	Power, transport, industry (iron & steel industry, chemical industry, non-metallic minerals, pulp and paper industry, food and beverages, non-ferrous metals, textiles, production and usage of F-gases, solvents and product usage), residential and service sectors, agriculture and non-CO_2 emissions, waste and water, LULUCF For the industrial sub-sectors addressed in detail, CO_2 and non-CO_2 emissions are differentiated. They are calculated based on activity data and detailed information on energy inputs.
Geography:	Germany
Time horizon:	2050
Modelling approach:	The study does not apply a typical modelling approach. It rather uses a detailed and systematic information basis of the status quo, applies structural and framework data developments and constructs a greenhouse gas-neutral scenario for 2050 by switching

	to renewable energy forms and partly by allowing for changes in consumption and production structure (e.g. switch from primary to secondary production).
General Assumptions:	GDP is assumed to increase by 0.7% p.a. on average. Growth in the industrial sectors is based on GDP growth, but slightly adapted and translated into activity changes and quality increases. As a result, activity data is kept constant for steel, cement, glass, pulp and paper and textiles, assumed to increase by 30% for non-ferrous metals, assumed to increase by 80% for chemicals, and assumed to decrease for lime (-30%). For food and beverages different scenarios were looked at. CCS is not included in the scenario. Instead, the scenario assumes availability of best available technologies and significant technological progress of already existing technologies, but no new inventions.
Other aspects	The focus of the study is Germany, interdependencies with other European countries are not taken into account. At the same time, it is explicitly stated that the industrial structure and import and export patterns as well as standard of living are assumed to remain similar to today's. Not explicitly stated is the origin of synthetic energy carriers. Changes in consumption are assumed only in those sectors where they are absolutely necessary to reach greenhouse gas-neutrality.

3.1.4.1 Scenario descriptions and main assumptions and main mitigation results achieved in the scenarios

The study includes one scenario and describes that in more detail. All sectors and GHGs are addressed. Main assumptions for the construction of the scenario are:

- Development of a target scenario, i.e. the transformation process, related economic considerations or the selection of appropriate policy instruments are not part of the analysis
- Germany remains an exporting industrialized country with average annual GDP growth of 0.7%
- Significant technological progress with regards to already existing energy efficiency and GHG abatement technologies, but no new inventions (in particular no use of CCS technology and no use of nuclear power plants)
- No changes in behaviour with the exception of nutrition
- Reduction of emissions by 95% below 1990 levels (remaining emissions in 2050: 60 Mt)
- Population is assumed to decrease by about 12.5% by 2050 to approximately 72.2 million

In total, a reduction of emissions by 95% can be achieved without using CCS (neither in the power sector nor in the industry sector). Instead, the scenario uses a large amount of renewably produced hydrocarbons (i.e. methane for use in the iron/steel and chemical industry - along with the transport sector)[8]. GHG-neutral CO_2 is required for the production of synthetic carbon-neutral hydrocarbons. Whether the amount of GHG-neutral CO2 could be produced within Germany or would have to be imported is not clarified within the study.

3.1.4.2 Overview of scenario results

The below table presents the results related to the industrial sectors. The analysis includes CO_2 as well as non-CO_2 GHGs

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[8] Alternatively, hydrogen produced with renewable energy could be used instead of methane, but this would require larger infrastructure changes. Since the production of methane requires more energy than the production of hydrogen, the assumption that methane is used implies a conservative (higher) estimate for total energy demand (see page 62 and 73 in UBA 2014, and page 15 in the associated background paper https://www.umweltbundesamt.de/en/publikationen/germany-2050-a-greenhouse-gas-neutral-country

Table 10: UBA 2014 Overview of scenario results

Industry sectors	Emission levels (2050) compared to 2010	Assumptions	Production & Implemented Technologies
Steel industry	-99.7%	Constant production in 2050 relative to 2010, 30% growth in GVA is interpreted to be qualitative, but not quantitative in terms of increased production figures (.	Direct reduction of iron, use of renewable methane (or alternatively hydrogen), increase in scrap recycling, no primary steel production in BOFs, only EAF steel production
Non-ferrous metals	-100%	Until 2050 0.7% growth in activity data → 3.8 m t non-ferrous metals, 5.9 m t semi-finished goods	Significant increase in recycling (90% for main non-ferrous metals), use of renewable methane and renewable electricity
Foundries	-100%	Iron & steel foundries: 0.7% growth p.a. (+34% compared to 2008), non-ferrous metal foundries: 1.6% p.a. (+95% compared to 2008); production efficiency increase to 90% on average	Use of electric foundries, use of renewable methane for production of cast iron
Chemical industry	-98.7%	Production increase by 80% by 2050 (2.2% p.a.)	Use of renewable methane or, alternatively, hydrogen as substitute for oil derivatives and natural gas, substitution of coal by zeolithes
Cement industry	-79.8%	Production remains constant	50% production of low-carbon cement, only 50% production of conventional cement Reduction of clinker ratio from 0.77 to 0.71 Use of renewable methane
Glass industry	-94.1%	Production remains constant	Increase in use of waste glass (cullet)
Lime industry	-64.8%	Production decrease by 31% by 2050	Use of renewable methane No reduction of process-related emissions
Paper and pulp industry	-100%	Production remains constant	Increase in energy efficiency Increase in recycling quota Use of renewable methane
Food industry	-100%		Almost complete use of electricity
Textile industry	-100%	Production remains constant	Use of renewable methane, hydrogen and electricity
F gases	-92%		Realization of all of today's technological possibilities for reduction of F gases

Industry sectors	Emission levels (2050) compared to 2010	Assumptions	Production & Implemented Technologies
Product use and solvents	-50%		Solvents from renewable resources Increase in efficiency of solvent usage No N_2O usage in anaesthesia

3.1.4.3 Technology overview

The study discusses in detail technological mitigation options for the different industry sectors. CCS is explicitly excluded from the study. While technological progress is taken into account for energy efficiency and mitigation technologies, no inventions (i.e. development of new technologies) are considered in the scenarios. That definition includes, however, for example low-carbon cement, a product that is not yet available today.

3.1.5 BMUB 2015 Climate Protection Scenario 2050

BMUB 2015 Climate Protection Scenario 2050 – second round (Klimaschutzszenario 2050, 2. Modellierungsrunde), 467 pages.

Table 11: BMUB 2015 Climate Protection Scenario 2050, 2nd round, general information

Carried out by:	Oeko-Institut and Fraunhofer Institute for Systems and Innovation Research (ISI)
Commissioned by:	German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU)[9]
Link:	https://www.oeko.de/oekodoc/2451/2015-608-de.pdf
Range of emission reductions achieved	-80 to -95% (2050 vs. 1990)
Aim:	The study develops ambitious climate protection scenarios for Germany for the year 2050 and analyses measures and strategies to reach those targets. The study is target-oriented, i.e. it starts with the target values and develops the measures necessary to reach those targets. It is model-based, i.e. for all relevant sectors techno-economic models are being applied.
Sectoral coverage:	Power, transport, industry (differentiated by all relevant energy-intensive industries), residential and service sectors, agriculture and non-CO_2 emissions, waste and water, LULUCF For the industrial sub-sectors addressed in detail CO_2 and non-CO_2 emissions are detailed. They are calculated with the bottom-up model FORECAST
Geography:	Germany
Time horizon:	2050
Modelling approach:	The study is model-based. Several techno-economic sector models as well as two macroeconomic models are being applied. An integration model is being used to bring

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[9] From 2013 to 2017, the ministry was also responsible for the building sector, and was therefore called Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMUB).

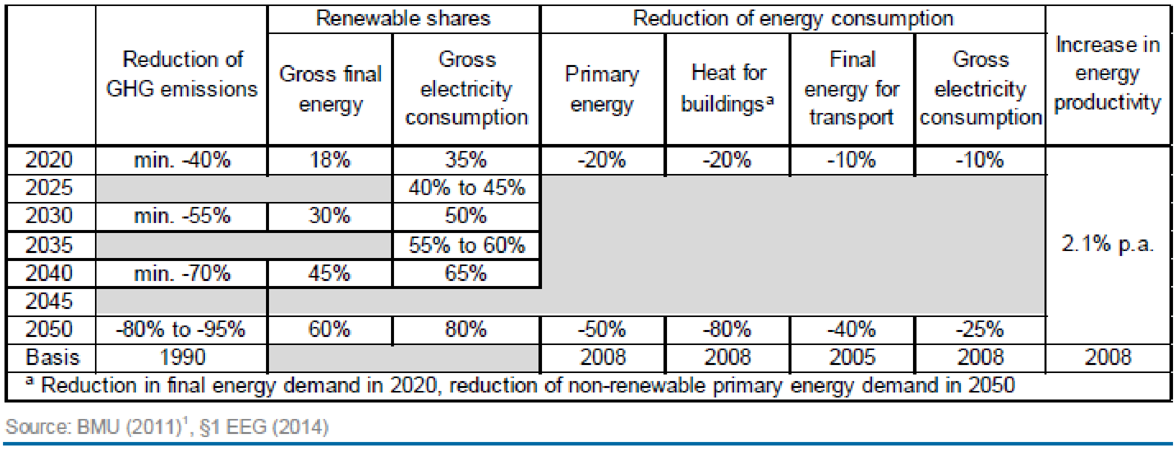
	together results for the different sectors and ensure consistency of the scenario. The energy-demand model FORECAST is applied to calculate the scenarios for the industry sectors. It allows for inclusion of technology developments and their effects on energy demand and emissions. It further allows taking into account barriers that may prevent investments into new technologies from taking place.
General Assumptions:	GDP is assumed to increase by 0.93% p.a. on between 2010 and 2030 and by 0.61% between 2030 and 2050. Population is assumed to decrease to 74 million by 2050. Gross value added is calculated with ASTRA-D. Accordingly, GVA for manufacturing industries increases from 444 bn €2010 in 2010 to 593 bn €2010 in 2050 (ca. 0.7% per year). That is, the study assumes Germany to remain an important production location, competitiveness of industry is retained.
Other aspects	Model results are being compared between different ambition levels as well as between different modelling rounds. In total, three modelling rounds take place over a timeframe of six years.

3.1.5.1 Scenario descriptions and main assumptions and main mitigation results achieved in the scenarios

The study includes three scenarios with different levels of ambition: an existing measures scenario, an 80% reduction scenario and a 95% reduction scenario, covering all sectors and GHGs. Scenarios vary mainly by the level of ambition. However, one major difference exists with regards to technology availability: for the 95% scenario the CCS technology is assumed to be available to allow for the ambitious reduction target to be met. That is not the case in the other scenarios.

- Existing measures scenario: The scenario accounts for all measures implemented by October 2012, projecting them forward to the year 2050. It presents the state of energy and climate policy framework currently in place.
- Climate protection scenario 80: In this scenario, the targets from the German government's energy concept are being met regarding GHGs (less ambitious end of the target range), renewable energies and energy efficiency.
- Climate protection scenario 95: In this scenario, the targets from the German government's energy concept are being met regarding GHGs, targeting at the more ambitious end of the target range, i.e. 95%. Also, targets for renewable energies and energy efficiency are met.

Figure 3: Framework for the climate protection scenarios



		Renewable shares		Reduction of energy consumption				
	Reduction of GHG emissions	Gross final energy	Gross electricity consumption	Primary energy	Heat for buildings^a	Final energy for transport	Gross electricity consumption	Increase in energy productivity
2020	min. -40%	18%	35%	-20%	-20%	-10%	-10%	2.1% p.a.
2025			40% to 45%					
2030	min. -55%	30%	50%					
2035			55% to 60%					
2040	min. -70%	45%	65%					
2045								
2050	-80% to -95%	60%	80%	-50%	-80%	-40%	-25%	
Basis	1990			2008	2008	2005	2008	2008

^{a} Reduction in final energy demand in 2020, reduction of non-renewable primary energy demand in 2050

Source: BMU (2011)^1, §1 EEG (2014)

Source: BMUB 2015

3.1.5.2 Overview of scenario results

Focusing on the industry sector in the study shows that significant differences exist between the scenarios. The following table presents GHG emissions from the industry sector in 2050 in the different scenarios:

Table 12: BMUB 2015 Overview of scenario results

5.	EMS [Mt CO$_2$e]	CS 80 [Mt CO$_2$e]	CS 95 [Mt CO$_2$e]
Industry – energy related emissions	74.9	33.9	-3.5
Industry – process related	55.4	36.4	4.6
Industry – total	130.3	70.3	1.1

The comparison shows that emissions from industry are significantly reduced in both climate protection scenarios. It also shows that in the CS 80 scenario, when the CCS technology is not available, the emission reductions in the industry sector are significant, but well below the average reduction target of 80%. In contrast, in the CS95 scenario, emissions from industry are almost completely mitigated or captured and stored underground. The use of biomass in combination with CCS allows the industry sector to generate negative energy-related emissions.

3.1.5.3 Technology overview

As important factors for reducing emissions in industry sectors the study names activity data and – related to that – material efficiency and recycling. Accordingly the physical production in many sectors and in particular in primary production routes is significantly reduced (detailed data is available in the study, table 6 summarises main products). An exception is the chemical industry, where activity data increases for many products. At the same time share or secondary production routes increases for all major energy-intensive products (see Table 13).

Table 13: BMUB 2015 Assumptions on production figures and recycling

	Production data [kt]			Share of secondary production routes/clinker ratio	
	2010	**EMS & CS 80**	**CS 95**	**EMS & CS 80**	**CS 95**
BOF steel	30 615	22 060	18 861	45%	45%
Primary aluminium	403	323	268	73%	77%
Primary copper	402	398	358	43%	49%
Primary zinc	238	239	205	---	---
Paper	22 509	24 978	23 729	92%	95%
Container glass	4 379	4 845	4 603	---	---
Cement clinker	24 541	17 695	14 289	61%	52%
Ammoniac	3 128	3 142	2 984	---	---
Chlorine	4 539	4 849	4 607	---	---

	Production data [kt]			Share of secondary production routes/clinker ratio	
Hydrogen	7 312	9 615	9 615	---	---
Adipic acid	358	592	592	---	---
Nitric acid	2 513	3 814	3 814	---	---

One focus of the study is on energy efficiency. In total, final energy demand in industry decreases from 2,402PJ in 2010 to 1,756 PJ in the CS 80 and to 1,440PJ in the CS 95 scenario. In addition, the share of electricity in industry increases significantly.

CCS is the key technology that allows the reduction of process emissions in the CS 95 scenario. In combination with biomass it leads to negative energy-related emissions in industry in 2050. For emissions from adipic and nitric acid, the scenario assumes a complete implementation of mitigation technologies for these two products, reducing the resulting N_2O emissions

3.1.6 DECC 2015 Industrial Decarbonisation & Energy Efficiency Roadmaps

DECC 2015 Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050 – Cross Sector Summary, 31 pages

Table 12: DECC 2015 general information

Carried out by:	Parsons Brinckerhoff and DNV GL
Commissioned by	Department of Energy and Climate Change (DECC) and the Department for Business, Innovation and Skills (BIS)
Link:	https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/419912/Cross_Sector_Summary_Report.pdf
Range of emission reductions achieved	Iron & Steel: -60% (2050 vs. 2012, max Tech Pathway) Pulp & Paper: -98% (2050 vs. 2012, max Tech Pathway) Chemicals: -79 to -88% (2050 vs. 2012, max Tech Pathway) Cement: -33 to -62% (2050 vs. 2012, max Tech Pathway) Ceramics: -60% (2050 vs. 2012, max Tech Pathway)
Aim:	This report aims to create a cross sector summary of eight individual industry sector reports. Those reports are aiming to analyse the potential for CO_2 emission reduction and the challenges to realize those reductions.
Sectoral coverage:	Cement, ceramics, chemicals, food and drink, glass, iron and steel, oil refining, and pulp and paper
Scope:	CO_2 emissions from production and manufacturing sites which includes combustion fuel, process and indirect emissions from purchased electricity are in the scope. Energy demand reduction from energy efficiency measures are outside of the scope of quantitative analysis, however included in the given opportunities
Geography:	UK
Time horizon:	2012-2050
Modelling approach:	The model provides a simplified top-down representation of sectors to which the possible emission reduction options are applied. It does not provide the least cost or optimal pathway. For each sector five different pathways are analysed. Three of the pathways are created to explore ways to deliver certain decarbonization bands by 2050 compared to base year; 20-40%, 40-60% and 60-80%

	One of the remaining two pathways analyses the Business as Usual (BAU) pathway without any further measures taken to reduce emissions. The other one is to calculate the emission level when the maximum potential of technologies is realized. The pathways are developed in an iterative manual process, not with a mathematical optimization process. All the pathways are tested under three scenarios, each includes different sets of conditions which may directly or indirectly affect the decarbonization ability of the sectors. These are “current trend”, “challenging world” and “collaborative growth”, defined by differing future electricity grid decarbonization, sector growth, energy cost and cost of carbon.
General Assumptions:	The model inputs and technology options are based on technology review, interviews and stakeholder inputs in workshops and sector meetings. If data could not be obtained through previously described channels, they are estimated by sector consultants. The uncertainties are not directly quantified however included by the sensitivity analysis especially in maximum technical scenarios. Deployment of options at five-year intervals is generally restricted to 25% steps unless otherwise indicated
Other aspects	The cross-sector report shows the results of pathways from “current trends” scenario which assumes low stable growth in the industries. The results from other scenarios can be obtained from individual sector reports.

3.1.6.1 Scenario description and main assumptions

In the cross-sector report, the combined results from three pathways, namely BAU, intermediate and max technology, under the “current trend scenario” are given. The results from detailed pathway analysis for all pathways under different scenarios are given in individual sector reports.

The assumptions for the “current trend scenario” are represented below as an example. The assumptions for the other scenarios and much more information on the individual sectors can be found in the Annexes of the individual sector reports of DECC.

Table 14: Assumptions in Current Trend Scenario

International consensus	Modest
International economic context	Slow growth in EU, stronger in world, relatively stable markets
Resource availability and prices	Competitive pressure on resources. Some volatile prices Central price trends.
International agreements on climate change	Slow progress on new agreements on emission reductions, all existing agreements adhered to.
General technical innovation	Modest innovation, incidental breakthroughs
Attitude of end consumers to sustainability and energy efficiency	Limited consumer demand for green products, efficiency efforts limited to economically viable improvements
Collaboration between sectors and organisations	Only incidental, opportunistic, short term cooperation
Demographics (world outlook)	Declining slowly in the west Modest growth elsewhere
World energy demand and supply outlook	Balanced but demand growth dependent on supplies of fossil fuels from new fields
UK economic outlook	Current OBR (Office of Budget Responsibility) growth assumption

International consensus	Modest
Carbon intensity of electricity	Stronger trend of electricity carbon intensity reduction 100g/kWh at 2030
Price of electricity	Central prices
Fossil Fuel	UEP (Updated energy production) central
Carbon Prices	UEP (Updated energy production) central carbon price
CCS availability	Technology does not become established until 2030
Low carbon process technology	New technology economically viable as expected

3.1.6.2 Overview of scenario results

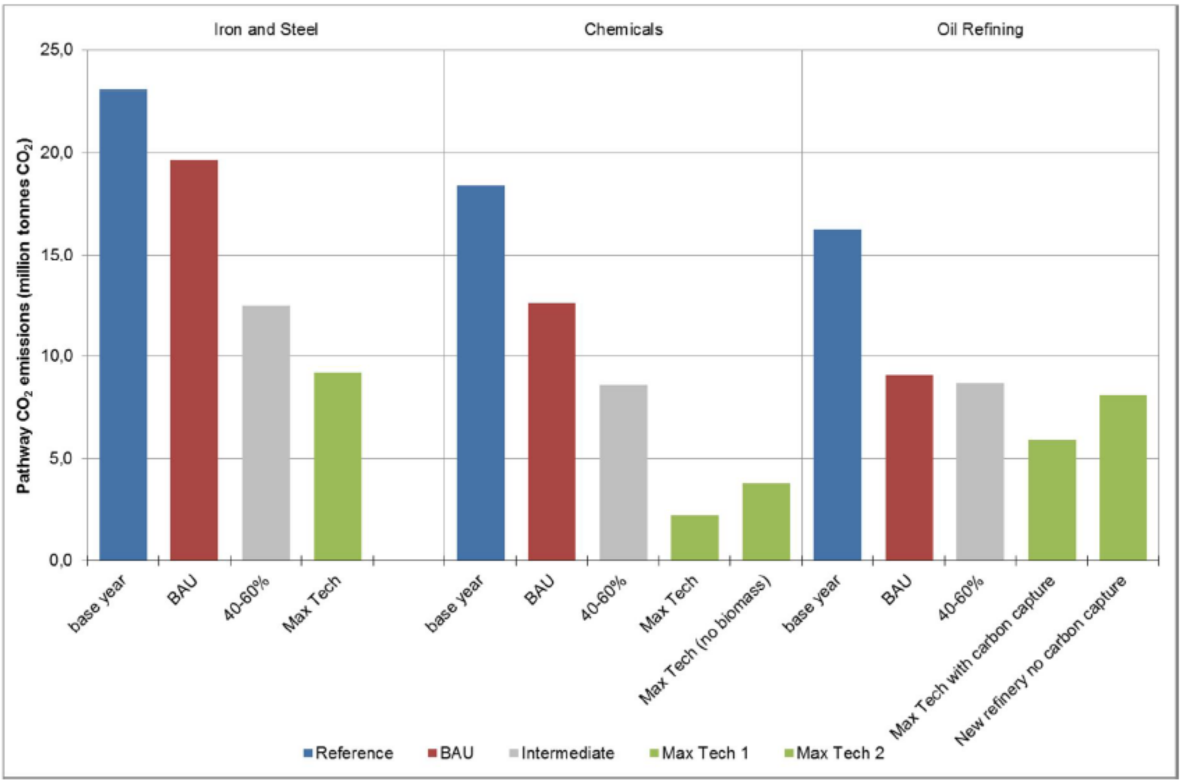
In the below table, combined results of eight sectors for BAU, max technology and intermediate pathways are represented. Under the table, more detailed results about individual sectors can be observed in the graphs.

Table 15: DECC 2015 overview of scenario results

Scenario	Emission levels (2050)	Assumptions	Production & Implemented Technologies
Business as Usual (BAU)	58 Million Tonnes in 2050 (28% reduction compared to 2012)	Current trend scenario assumptions. In BAU pathway, the technologies which are currently being deployed across the sectors are assumed to continue to be implemented to each plant or site when they reach the appropriate point for the deployment.	Most effective technologies; Electricity Grid decarbonisation (62% of total reduction) Energy efficiency (23%) Increased use of biomass (7%) Other technologies; CCS, Clustering, Fuel switching, Electrification of Heat, Material Efficiency
Intermediate reduction	42 Million Tonnes in 2050 (48% reduction compared to 2012)	Current trend scenario assumptions	Most effective technologies; Electricity Grid decarbonisation (37% of total reduction) Energy efficiency and heat recovery (23%) CCS (18%) Increased use of biomass (13%) Other technologies; Clustering, Fuel switching, Electrification of Heat, Material Efficiency
Maximum Technical Pathway	22 Million Tonnes in 2050 (73% reduction compared to 2012)	Current trend scenario assumptions Maximum technology pathway considers all the technologies which are at least in pilot phase and include them in respect to their technical limits. The other constraints are set aside. Other promising technologies which	Most effective technologies; CCS (37% of total reduction) Electricity Grid decarbonisation (25% of total reduction) Increased use of biomass (16%) Energy efficiency and heat recovery (13%) Other technologies;

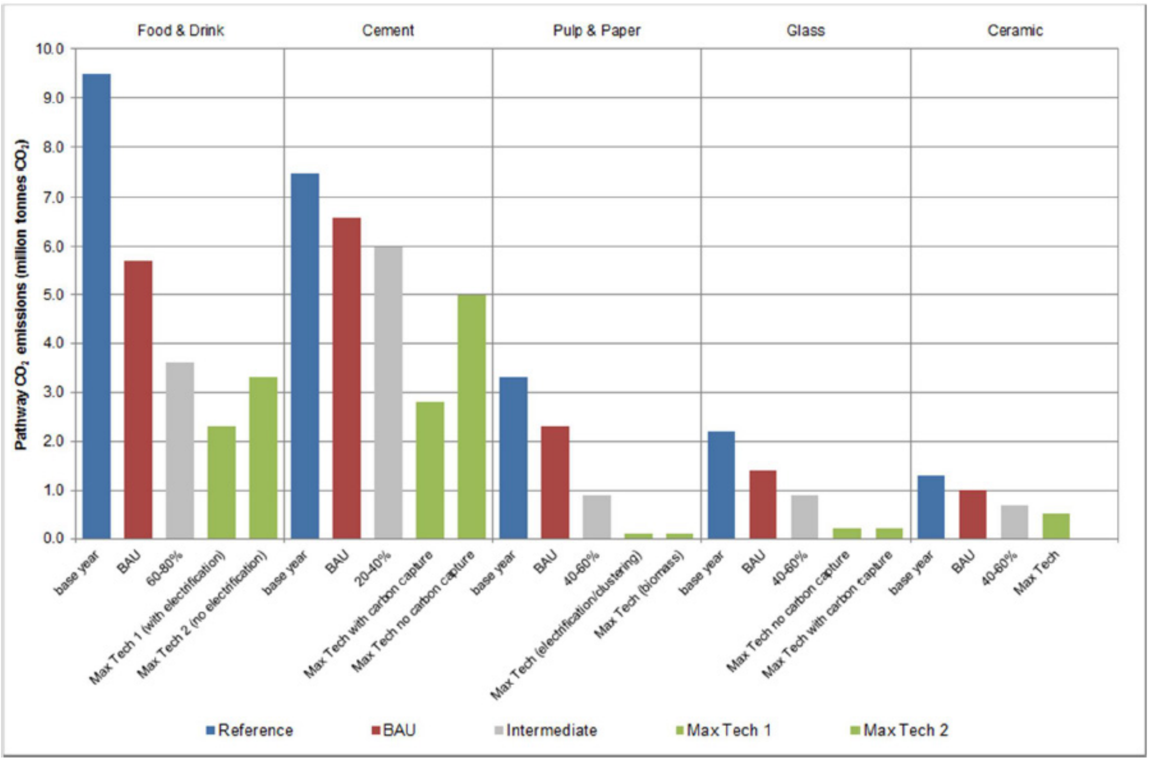
Scenario	Emission levels (2050)	Assumptions	Production & Implemented Technologies
		are not mature enough are not included Maximum utilization of biogenic material as fuel or feedstock assumes unlimited possibility	Clustering, Fuel switching, Electrification of Heat, Material Efficiency

Figure 4: **CO_2 emissions in different pathways for iron & steel, chemicals and oil refining in DECC 2015**



Source: DECC Cross sector report, p. 7

Figure 5: CO₂ emissions in different pathways for food & drink, cement, pulp & paper, glass and ceramics in DECC 2015



Source: DECC p. 7

3.1.6.3 Technology Overview

For technology information please refer to the individual sector sections.

3.1.6.4 Industry contribution in emission reduction in other industries

N/A

3.2 Iron & Steel Industry

3.2.1 Technology Overview

Currently in EU, liquid steel is made either through blast furnace basic oxygen furnace route (BF-BOF) where most of the carbon in hot metal is removed in a Basic Oxygen Steel plant, or through Electric Arc Furnace (EAF) where recycled scrap is used as input. In total, both technologies account for 98% of the total steel production in EU27. An alternative to the BF-BOF route is the smelting reduction converter (SR-BOF) route in which the blast furnace is replaced by a pre-reduction and a melter gasifier. The two main SR technologies are COREX and FINEX. A third route is the direct reduced-iron electric arc furnace route (DRI-EAF). Other iron and steel making processes so far have little significance in Europe (BCG 2013).

Several studies on abatement options in the Iron & Steel industry exist. Since technologies are similar, we describe the technologies separately. The technology overview tables can be found in the annex.

In EUROFER (2012), apart from the technologies in the EU, some other international initiatives to develop breakthrough technologies in order to reduce emission in the sector are presented. Those programs are:

- Course 50 in Japan involving two research areas: One for CO_2 reduction in blast furnaces and one to capture, separate and recover CO_2 from blast furnace gas. Both are estimated to be industrialized from 2030 onwards.
- POSCO in Korea is a firm researching in different areas including the adaptation of CCS in Smelting Reduction and ammonia-based scrubbing technology. They already set up a 1.5-Mt per year FINEX unit. A new FINEX unit with 2 MT per year is in progress.
- The American Iron and Steel Institute (AISI) program working on three areas: Molten Oxide Electrolysis, Hydrogen Flash Smelting, Paired Straight Hearth Furnace.
- The Brazilian steel industry that continues its development of a biomass steel production route based on sustainable plantations of eucalyptus trees, production of charcoal and small charcoal blast furnaces
- The Canadian Steel Producers Association (CSPA) that also focuses on the use of biomass in iron and steel making. The short term target is to replace PCI (pulverized coal injection) with charcoal injection, which can reduce the GHG emissions by 23%.

3.2.2 BCG 2013 Steel's contribution to low-carbon Europe

BCG 2013 Steel's contribution to a low-carbon Europe 2050, 49 pages

Table 16: BCG 2013, general information

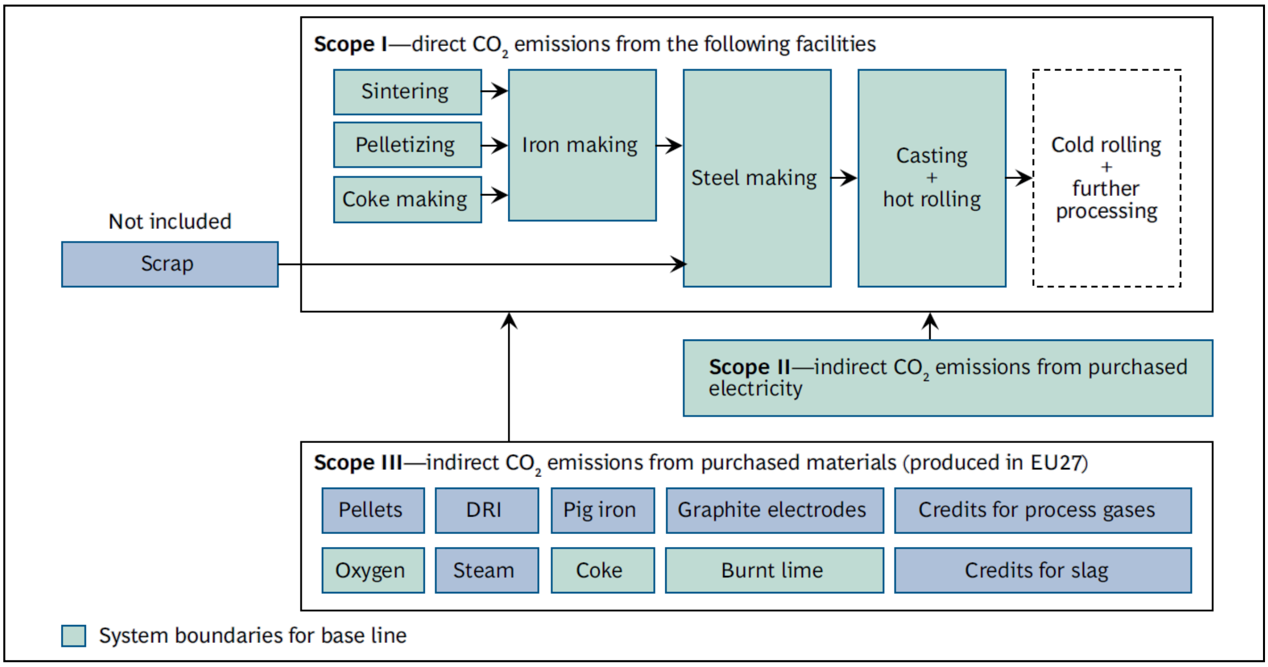
Carried out by:	The Boston Consulting Group and Steel Institute VDEh
Commissioned by	EUROFER
Link:	http://www.bcg.de/documents/file154633.pdf
Range of emission reductions achieved	+2% to -58% (2050 vs. 1990)
Aim:	The study presents a technical and economic perspective on steel's CO_2-mitigation potential examining which reduction technologies are available and the potential impact they can have between 2013 and 2050. Apart from steel production processes the study also analyses the effect of efficient applications of steel in other industries. The study claims that reaching a -80% cut in emissions is impossible in the steel industry and that replacing the mainly used BF-BOF process by scrap fed processes is not feasible. However, the study indicates that there is still substantial CO_2 emission reduction potential despite the estimated increase in production by 2050, by increasing the efficiency of current processes (such as EAF).
Sectoral coverage:	Iron and Steel
Scope:	The analysis includes direct emissions from processes, GHG generated from produced heat and electricity and indirect emissions from purchased electricity and from materials purchased within the EU27 such as coke, burnt lime, and O_2. Cold rolling and further processing (accounting for roughly 10% of emissions) are not included in the study because of lacking reliable data. An illustration of the scope can be found in Figure 6.
Geography:	EU27
Time horizon:	1990-2050
Modelling approach:	Calculations are based on the total carbon footprint of the EU27 steel industry (excluding ore extraction and transport, and several other indirect emissions from

	inputs, see illustration below), based on data from company reports. Emissions have been calculated bottom-up based on material flows along the value chain (combining specific emissions factors with the shares of the different production routes and the total steel production).
General Assumptions:	Steel production is expected to grow around 0.8% p.a. between 2013 and 2050 in order to meet the demand for steel in the EU27 resulting in 236 Mt Crude Steel (CS) production in 2050. A -60% reduction of emissions is estimated in the power sector compared to 1990.
Other aspects	12 Mt of the savings in total emissions result from decreased CO_2 intensity of electricity consumed in the scrap EAF route. This is ~ 45% of the lowest estimated savings and 7% of the savings in the highest savings scenario. In 1990 the total emission from iron & Steel industry under the scope of the study were 298 Mt CO_2.

3.2.2.1 Scenario descriptions and main assumptions

The following Figure 6 depicts the system boundaries of the BCG study. Both direct and indirect emissions (both from purchased electricity and from purchased materials) are considered (all green boxes). Emissions associated with the materials in blue boxes are excluded by BCG.

Figure 6: Scope of "Steel's contribution to low-carbon Europe"



The following paragraphs describe the differences between the several scenarios analysed.

The BCG study first presents four **technological scenarios** that analyse only the effect of different technologies without considering economic feasibility. The scenarios "Upper Boundary (Baseline) and "Lower theoretical boundary without CCUS" are then judged as not feasible under economical terms under any price condition.

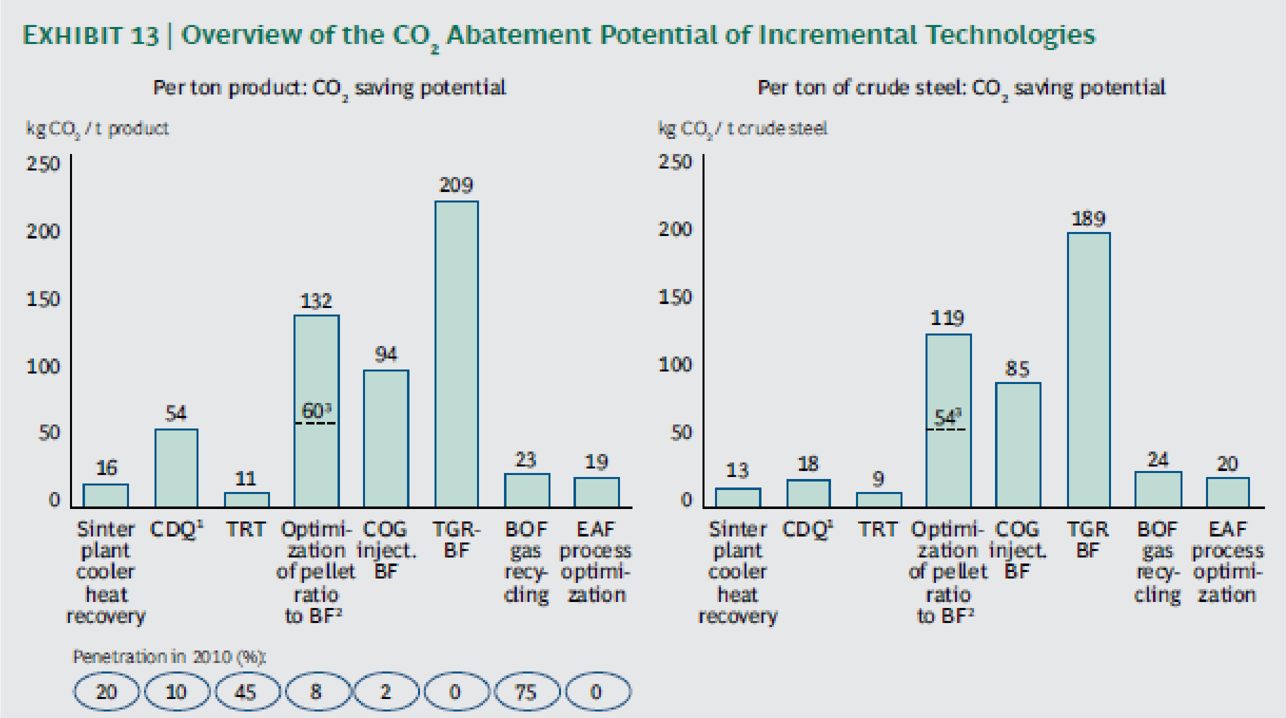
Additionally, two **economic scenarios** are investigated. They assume that 44% of steel production is produced via the Scrap – EAF route. The study applies different price levels of input factors (energy and material prices) and CO_2 to investigate the feasibility of using incremental technologies to improve existing BF routes and replacing existing BF – BOF plants by lower carbon technologies. The CO_2 prices in those scenarios are reflecting the total cost to offset the cost disadvantage of a new Greenfield plant replacing the BF – BOF plants with low carbon technologies compared to applying incremental technologies to existing plants. The share of the technologies in each scenario is unfortunately not given.

Furthermore, the “**Drop in Steel production**” scenario, investigates the effect of a production decrease. The scenario is considered as unrealistic and undesirable.

None of the scenarios gives any specific information about the electricity need of the sector or the different energy carriers in industrial energy demand.

The study applies several incremental technologies to reduce emissions. The following graph present the respective CO_2 abatement potential.

Figure 7: Abatement potential by technologies from BCG 2013



CDQ: Coke Dry Quenching, TRT: Top Gas Recovery Turbine, BF: Blast furnace, COG inject. BF: Coke oven gas (or other H2-rich reductants) injection in blast furnace, TGR-BF: Top gas recycling in blast furnace processes, BOF: Basic oxygen furnace, EAF: Electric arc furnace

3.2.2.2 Overview of scenario results

Table 17: BCG 2013 overview of scenario results

Scenario	Emission levels (2050)/change compared to 1990)	Assumptions	Production & Implemented Technologies
Upper Boundary (Baseline)	305 Mt CO_2 +2.3% compared to 1990	unchanged performance i.e. constant specific emissions and relative split between BF-BOF and Scrap-EAF route production level as sole variable	Production: 236 Mt CS (59% BF – BOF, 41% Scrap – EAF) No further BATs or innovative technologies (ITs) implemented

Scenario	Emission levels (2050)/change compared to 1990)	Assumptions	Production & Implemented Technologies
Feasible Upper Boundary	271 Mt CO_2 -9% compared to 1990	Emissions from both routes improve to the weighted average of top 50% of best performers through the shared best practices Scrap quality is not a limiting factor for the increase of scrap based steel production. quality requirements of some sectors limit the shift towards scrap based steel production.	Production: 236 Mt CS (56% BF – BOF, 44% Scrap – EAF) emission efficiency improves to weighted average of 50% best performers No additional BATs or Breakthrough technologies implemented
Lower theoretical boundary without CCUS	184 Mt CO_2 -38% compared to 1990	DRI-EAF has a specific CO_2 intensity of 1.2 t CO_2 /t CS in 2050 Hot charging of DRI becomes common practice by 2050 (emission reduction -2%) DRI-EAF gradually replaces BF – BOF until 2050 Incremental changes applied to BF – BOF before replacement Scrap – EAF process efficiency increases by 45 KWh/t CS (associated reduction in specific emissions of -3%)	Production: 236 Mt CS (11% BF – BOF, 44% Scrap – EAF, 45% DRI - EAF) shift towards DRI and EAF several efficiency improvements in BF-BOF
Lower theoretical boundary with CCUS	130 Mt CO_2 -56.3% compared to 1990	The relative specific final CO_2 emissions per ton of crude steel produced with CCUS are almost the same for all production routes (BF-BOF, DRI-EAF, SR–BOF)	Production: 236 Mt CS (44% Scrap – EAF, 56% BF – BOF with TGR, DRI – EAF, SR – BOF) regardless of price CCUS technology is fully implemented by 2050 starting from 2030
Economic Scenario – reference price	263 Mt CO_2 -12% compared to 1990	Input factor prices are adjusted for inflation CO_2 prices of min. 259 €/t CO_2 to offset low carbon facilities	Production: 236 Mt CS (44% EAF, %56 shared between DRI – EAF, BF – BOF, SR – BOF) Economically feasible BATs implemented; sinter-plant-cooler heat recovery, BF top gas pressure recovery turbine (TRT) and EAF process-efficiency improvements
Economic Scenario – medium price	260 Mt CO_2 -13% compared to 1990	Input factor prices double in 2050 compared to 2010 CO_2 prices of min. 393 €/t CO_2 to offset low carbon facilities	Production: 236 Mt CS (44% EAF, %56 shared between DRI – EAF, BF – BOF, SR – BOF) Economically feasible BATs implemented; sinter-plant-cooler heat recovery, BF top gas pressure recovery turbine (TRT) and EAF process-efficiency improvements

Scenario	Emission levels (2050)/change compared to 1990)	Assumptions	Production & Implemented Technologies
Economic Scenario – high price	256 Mt CO_2 -14% compared to 1990	Input factor prices are fivefold higher in 2050 than in 2010 CO_2 prices of min. 706 € / t CO_2 to offset low carbon facilities	Production: 236 Mt CS (44% EAF, 56% shared between DRI – EAF, BF – BOF, SR – BOF) Economically feasible BATs implemented; sinter-plant-cooler heat recovery, BF top gas pressure recovery turbine (TRT) and EAF process-efficiency improvements, B OF gas recycling and CDQ
Drop in production	108 Mt CO_2 without CCUS -64% compared to 1990 76 Mt CO_2 with CCUS -74% compared to 1990	production decrease to 2009 level (139 Mt CS)	Production: 139 Mt CS No information about implemented technologies

3.2.2.3 Industry contribution in emission reduction in other industries

Apart from the emission reduction potentials in the steel sector, the study analyses the emission reduction potential of innovative steel usage in three different sectors via eight case studies.

- Energy sector: efficient fossil fuel power plants, offshore wind turbines, bioenergy power plant, efficient transformers, efficient e-motors.
- Traffic: weight reduction in cars, weight reduction in trucks
- Household and industry: Combined Heat and Power

The projection is done by calculating the emission savings from the more efficient application of steel in the above sectors in the EU compared with the emissions during production. The result is a reduction of -440 Mt CO_2 emissions while producing an extra of 70 Mt CO_2.

3.2.3 JRC 2012 Energy efficiency and CO_2 emissions in Iron and Steel

JRC 2012 A Prospective Scenarios on Energy Efficiency and CO_2 Emissions in the EU Iron & Steel Industry, 50 pages

Table 18: JRC 2012, general information

Carried out by:	Joint research centre, Institute for Energy and Transport, Petten, NL
Commissioned by	European Commission
Link:	http://www.eurosfaire.prd.fr/7pc/documents/1355390994_jrc_green_steel.pdf
Range of emission reductions achieved	-54% to -58% (2050 vs. 1990)

Aim:	The study analyses the effect of new technologies on energy consumption and CO_2 emissions in the steel sector in different scenarios based on fuel, resource and CO_2 prices.
Sectoral coverage:	Iron & Steel
Geography:	EU27
Time horizon:	2010-2030
Modelling approach:	Energy and CO_2-emission are modelled using a bottom-up model at the facility level of the European Iron & Steel industry. The original plant data does not contain information on different specific energy consumption or emissions. To model the diversity of plants therefore, the data have been combined with the benchmarking curves for CO_2 emissions from the European Commission to calibrate data for the first year of the simulation. Prices for resources, electricity and CO_2 enter the model as exogenous variables. The same holds for consumption, production and scrap availability. The study contains three different scenarios: a baseline and two alternative scenarios (AS). AS 1 analyses the impact of higher prices for energy and resources. AS 2 studies the effect of higher CO_2 prices.
General Assumptions:	Consumption of finished steel is expected to grow by 2% p.a. for the EU27 from 2009-2030. Production of finished steel is expected to grow by 1.8% annually for the EU27 from 2009-2030 which would amount to around 260 Mt Crude Steel in 2030. Around additional 14 million tonnes of scrap per year is estimated from 2009 until 2030. Baseline scenario: CO_2 prices are assumed to rise from 11 €/t CO_2 in 2010 to 39 €/t CO_2 in 2030. Estimated energy and material price details are given in the section 3.2.4 Scenario descriptions and main assumptions
Other aspects	CO_2 emissions under the scope of the study was 185 Mt CO_2 in 2010

3.2.4 Scenario descriptions and main assumptions

In the study, the results from changing only one variable at a time from the projections are investigated.

In the **Baseline Scenario,** the results from projected energy, resource and CO_2 prices, production and demand, scrap availability are reflected.

Alternative Scenario 1 (2x Fuel) and **(5x Fuel)** are investigating the changes in energy consumption and emissions in case of doubled and fivefold increase in energy and resource prices, respectively, compared to the baseline scenario. The other variables are not changed. The price differences affect the feasibility of BATs and ITs which eventually changes the results.

In **Alternative Scenario 2 (100 €/t CO_2)** and **(200 €/t CO_2)** the changing variable is the CO_2 price in 2030. The first scenario investigates the effects of a CO_2 price increase to €100/t CO_2 while the second scenario considers a CO_2 price of 200 €/t CO_2.

Table 19: JRC 2012, estimated energy and material price

Resource	Price 2010	Annual growth rate
Electricity	70 €/MWh	0.81%
Natural gas	219 €/km^3	1.98%

Resource	Price 2010	Annual growth rate
Oxygen	93 €/kNm^3	1.00%
Steam	0 €/t	n.a.
Coke	376 €/t	1.20%
Pellet	133 €/t	1.20%
Coal	170 €/t	1.64%
Iron ore	106 €/t	1.20%
Scrap	255 €/t	1.20%
Limestone	20 €/t	1.20%
Burnt lime	100 €/t	1.20%
Tar	175 €/t	1.20%
EAF slag	8 €/t	1.20%
BOS slag	8 €/t	1.20%
Granulated BF slag	8 €/t	1.20%

3.2.4.1 Overview of scenario results

Table 20: JRC 2012 overview of scenario results

Scenario	Emission levels & Energy Consumption (2030)*	Assumptions	Production & Implemented Technologies
Baseline Scenario	Emissions: 161 Mt CO_2, savings associated with: 45% iron and steel industry 55% in associated power plants Energy Consumption: 1579.2 PJ, savings are associated with: 87% iron and steel industry 13% in associated power plants	In line with general assumptions 2010–2020: Only BATs are incorporated 2020–2030: IT technologies are also implemented	7 BAT and 2 IT Technologies are most suitable: BATs (account for 21.2% emissions reduction, 56.7% energy consumption reduction); Most effective: Scrap pre-heating, Pulverised coal injection – Iron ore, State-of-the-Art power plant (after 2028) Other technologies: Optimized sinter-pellet ratio – iron making, Oxy fuel burners heat recovery, Bell-less-top ITs (account for 78.8% emission reduction, 43.3% energy consumption reduction); Top gas recycling Blast Furnace (15 retrofit), CCS in Power Plant (39 retrofit)
Alternative Scenario 1 (2x Fuel prices)	Emissions: 161 Mt CO_2 Energy Consumption: 1574 PJ	Analyses the impact of doubling the prices of energy and resources compared to baseline	6 BAT and 3 IT Technologies are most suitable: BATs (account for 19.2% emissions reduction, 30.2% energy consumption reduction); Same BATs as in baseline scenario excluding State-of-the-Art power plant

Scenario	Emission levels & Energy Consumption (2030)*	Assumptions	Production & Implemented Technologies
		Other assumptions are in line with general assumption	ITs (account for 80.8% emissions reduction, 69.8% energy consumption reduction); Top gas recycling Blast Furnace (29 retrofit), CCS in Power Plant (27 retrofit), HYL (1 facility)
Alternative Scenario 1 (5x Fuel prices)	Emissions: 157 Mt CO_2 Energy Consumption: 1566.5 PJ	Analyses the impact of fivefold increase of the prices of energy and resources compared to baseline Other assumptions are in line with general assumption	6 BAT and 3 IT Technologies are most suitable: BATs (account for 18.9% emissions reduction, 32.3% energy consumption reduction); Same BATs as in baseline scenario excluding State-of-the-Art power plant ITs (account for 81.1% emissions reduction, 67.7% energy consumption reduction); Top gas recycling Blast Furnace (20 retrofit), CCS in Power Plant (12 retrofit), HYL (5 facility)
Alternative Scenario 2 (100€ /t CO_2)	Emissions 158 Mt CO_2 Energy Consumption 1573 PJ	Analyses the effect of CO_2 prices considering the price increase linearly from 11 €/t CO_2 to 100€/t CO_2 Other assumptions are in line with general assumption	7 BAT and 3 IT Technologies are most suitable: BATs (account for 24.5% emissions reduction, 72.6% energy consumption reduction); Same BATs in baseline scenario with more State-of-the-Art Power Plants (18 retrofit) ITs (account for 75.5% emissions reduction, 27.4% energy consumption reduction); Top gas recycling Blast Furnace (5 retrofit), CCS in Power Plant (41 retrofit), Top gas recycling Blast Furnace & CCS
Alternative Scenario 2 (200€-CO_2)	Emissions 149 Mt CO_2 Energy Consumption 1570.4 PJ	Analyses the effect of CO_2 prices considering the price increase linearly from 11 €/t CO_2 to 200€/t CO_2 Other assumptions are in line with general assumption	7 BAT and 3 IT Technologies are most suitable: BATs (account for 21.6% emissions reduction, 84.1% energy consumption reduction); Same BATs in baseline scenario with more State-of-the-Art Power Plants (31 retrofit) ITs (account for 78.4% emissions reduction, 15.9% energy consumption reduction); Top gas recycling Blast Furnace (1 retrofit), CCS in Power Plant (41 retrofit), Top gas recycling Blast Furnace & CCS

(*) The numbers are approximate numbers which are derived from the graphs in the study. Emissions in 2010: 185 Mt CO_2, Energy consumption in 2010: 1482 PJ

3.2.5 EUROFER 2013 Steel low-carbon roadmap

EUROFER 2013 A steel roadmap for a low carbon Europe 2050, 35 pages

Table 21: EUROFER 2013, general information

Carried out by:	EUROFER (based on data and modelling from BCG and VDEh)
Commissioned by:	EUROFER
Link:	http://www.nocarbonnation.net/docs/roadmaps/2013-Steel_Roadmap.pdf
Range of emission reductions achieved	n.a. results are based on BCG 2013 see section 3.2.2
Aim:	In the context of the EU climate policy framework and the European Commission's low carbon roadmap, the EU steel industry contracted BCG and VDEh to assess the CO_2 mitigation potential of the EU27 steel industry up to the year 2050 (see above BCG 2013). This study is based on those results and a comparison to existing research. The motivation is that the EU has published ambitious emission reduction targets but it is not clear how each industrial sector will meet the objectives neither in technical terms nor in economic terms (cost implications and competitiveness effects). This study provides insights on emission reduction in the steel sector and gives policy recommendations. The study warns from investment leakage and recommends that EU should refrain from unilateral climate action and instead foster the development of breakthrough technologies.
Sectoral coverage:	Iron & steel
Geography:	EU27
Time horizon:	1990-2050
Modelling approach:	The study does not contain own modelling, but relates to BCG 2013 by BCG and VDEh
General Assumptions:	The paper is written mostly according to the findings of "Steel's contribution to a low-carbon Europe 2050" by BCG/VDEh a and comparing it with JRC study "Prospective Scenarios on Energy Efficiency and CO_2 Emissions in the EU Iron & Steel Industry" New capacity for primary steel making is not expected. The current capacities estimated to be enough for the demand in 2050.
Other aspects	

3.2.5.1 Scenario descriptions and main assumptions

The study itself does not use any own scenarios. It rather represents and compares the results from the JRC study and BCG study. An overview over the scenarios from those studies can be found in the previous sections.

3.2.6 CS IS 2014 Iron & Steel report

Climate Strategies 2014 Carbon Control and Competitiveness Post 2020: The Steel Report, 64 Pages

Table 22: CS IS 2014, general information

Carried out by:	Climate Strategies (output of Energy Intensive Industries project)
Commissioned by:	The governments of the Netherlands, Germany, France and the United Kingdom and from Heidelberg Cement and Tata Steel Europe

Link:	http://climatestrategies.org/wp-content/uploads/2014/10/20141014-steel-report---final-formatted-4.3.pdf
Range of emission reductions achieved	n.a.
Aim:	The study aims to point out the historical and current position of EU steel industry, the opportunities for mitigation, the barriers to reach the possible carbon reduction and the necessary policy suggestions.
Sectoral coverage:	Iron and Steel
Geography:	EU
Time horizon:	Not specified
Modelling approach:	The study does not have its own model for calculating emission reduction potentials. It rather represents the results of other studies.
General Assumptions:	
Other aspects	Today's steel demand is 20% below the level of 2007

3.2.6.1 Scenario descriptions and main assumptions

The study does not feature scenarios or quantitative results. It reviews and summarizes other studies.

Additional to the studies mentioned previously, this study gives more information about the recycling rates in the Steel industry. Recycling of steel in the automotive industry is nearly 100% and also a high rate of scrap steel is recycled from household appliances and structural steel construction. In contrast, because of the difficulty and high cost of retrieving steel from reinforced concrete the recycling rates for steel from reinforced concrete are low. Also recycling rates from packaging can be improved.

The study states that every tonne of recycled steel saves 1.1 tonne of iron ore, 0.6 tonne of coking coal and 0.05 tonne of limestone.

3.2.7 Van Ruijven et al. 2016 Long-term projections for global steel and cement industries

Van Ruijven et al. 2016 Long-term model-based projections of energy use and CO_2 emissions from the global steel and cement industries. Resources, Conservation and Recycling 112 (2016) 15–36, 22 Pages

Table 23: Van Ruijven et al. 2016, general information

Carried out by:	PBL Netherlands Environmental Assessment Agency National Center for Atmospheric Research (NCAR), Boulder, CO, USA Utrecht University, Copernicus Institute, Netherlands Ecofys, Utrecht, Netherlands. University of Geneva, Institute for Environmental Sciences and Forel Institute, Switzerland
Link:	http://www.pbl.nl/en/publications/long-term-model-based-projections-of-energy-use-and-co2-emissions-from-the-global-steel-and-cement-industries
Range of emission reductions achieved	-60% to -90% (2050 vs. 1990) (steel) -25% to -78% (2050 vs. 1990) (cement)

Aim:	The study presents a model to analyse energy and emission reduction potentials globally in steel and cement sector and the results for different carbon tax and technology improvement scenarios.The baseline scenario shows a rapid increase in emissions in the next decades followed by a decrease below 2010 levels in 2050 by more efficient production technologies. The availability of CCS and an increased carbon price can lead to a considerable additional reduction in both the cement and the iron and steel industry.
Sectoral coverage:	Iron and Steel, cement
Geography:	Global with a focus on Western Europe, USA, India, China,
Time horizon:	2010 to 2020 and 2050 (1971 levels are also shown)
Modelling approach:	The model which projects consumption and production of steel and cement industry in 26 world regions[10] is embedded in IMAGE global integrated assessment model. The model covers the full chain from population and income as driving forces for economic activity, to materials consumption and technology choice that then determine production capacity, energy use and CO_2 emissions. Trade is also considered.
General Assumptions:	The scenarios include a carbon tax to be introduced in 2020 with an annual increase of 4% and the (price-enabled) usage of CCS and other technologies. A maximum share of 90% of the EAF process is assumed if scrap is abundant. Scrap is not internationally traded. Until 2030, a linearly decreasing additional cost markup is assumed on CCS technology. All other costs are constant
Other aspects	Global emissions from fuel use in steel production in 2010 are 3250 Mt CO_2.

3.2.7.1 Scenario descriptions and main assumptions

The scenarios are based on the Shared Socioeconomic Pathway 2 scenario (Chateau et al., 2015) where global population rises from 6.9 billion people in 2005 to more than 9 billion people in 2050. Global GDP/Capita in purchasing power parity increases from $10,000 in 2005 to around $26,000 by 2050. Also global demand for steel and cement increases sharply in the first decades with a decreasing growth rate after 2030.

Under those assumptions three scenarios are analysed in the study with different carbon tax rates applied additional to a baseline scenario. The initial tax amounts in the different scenarios starting from 2020 are 20 $/t CO_2, 50 $/t CO_2 and 100 $/t CO_2 with an increase of 4% per year.

3.2.7.2 Overview of scenario results

In the study, the quantitative emission results for the mitigation scenarios are only given explicitly for the global scenario. However, figures are provided for all regions included in the modelling to get a feeling for the pattern. The representation of technology choices in different scenarios for Western Europe can be found in Figure 8.

In the baseline scenario, the standard BF-BOF routes remains to have a substantial share (nearly 30%) of production capacity in 2050. COREX has more than 10% and scrap based EAF is the dominant production routes with more than 50%.

At a CO_2-price path starting at 20 $/t CO_2, COREX in combination with CCS gains more importance both globally and in Western Europe (more than 25% of capacity) and the standard BF-BOF route on the global level only remains with a very small share of less than 5%. Instead, “primary EAF” (direct

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[10] From the 26 regions, main focus of the paper is “USA, Western Europe, India and China“

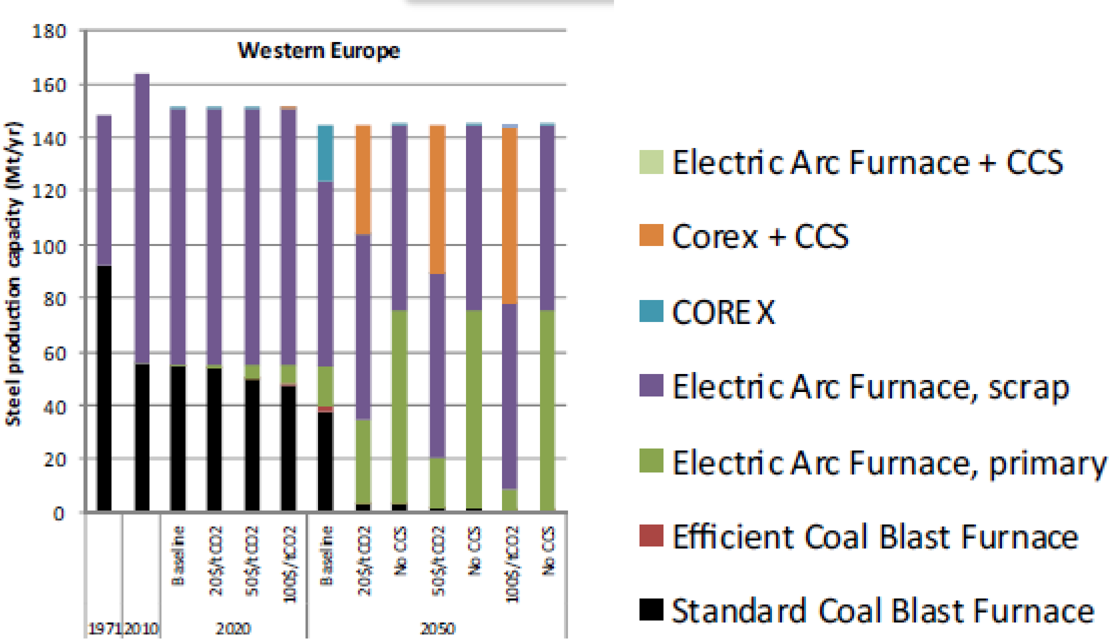
primary steel production combined with EAF) gains importance. The same trends increase at higher CO_2-prices.

When CCS is excluded from the eligible technologies, then globally as well as in Western Europe roughly 50% of the production capacity is scrap EAF and the remaining 50% is primary EAF using bioenergy and natural gas (see van Ruijven et al. 2016, figures 5 and 6).

Table 24: Van Ruijven et al. 2016 overview of scenario results

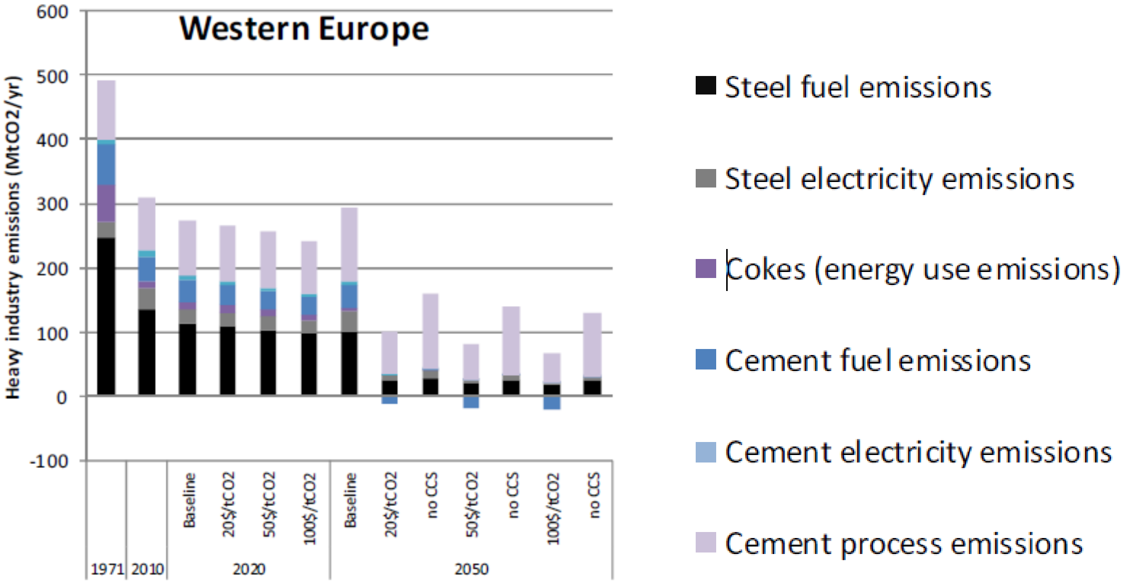
Scenario	Emission levels (2050)/change compared to 2010)	Assumptions	Production & Implemented Technologies
Baseline	**Globally;** 2,500 Mt CO_2, 23% lower **US;** 100 MtCO_2, 33% lower **Western EU;** 170 MtCO_2, 43% lower **China;** 700 MtCO_2, 58% lower **India;** 520 MtCO_2, 225% higher	No further policies regarding emission reduction	Share of efficient production technologies slightly increases: Share of the standard BF – BOF route around 30% Share of scrap EAF greater than 50% COREX 10%
20$ / tCO_2	**Globally without CCS;** 1000 MtCO_2, 69% lower **Globally with CCS;** 750 MtCO_2, 77% lower	A carbon tax of 20$ / tCO_2 is introduced globally starting from 2020 with annual increase of 4% ($65 in 2050)	Efficiency measures in short term, COREX and CCS in long term
50$ / tCO_2	Between 20$ and 100$ scenarios	A carbon tax of 50$ / tCO_2 is introduced globally starting from 2020 with annual increase of 4% ($162 in 2050) Fully decarbonized power sector	When CCS available; a mixture of COREX-CCS and EAF (with CCS) technologies. When CCS is not available, EAF is dominating
100$ / tCO_2	**Globally without CCS;** 500 MtCO_2, 85% lower **Globally with CCS;** 250 MtCO_2, 92% lower than 2010	A carbon tax of 100$ / tCO_2 is introduced globally starting from 2020 with annual increase of 4% ($324 in 2050) Fully decarbonized power sector	

Figure 8: Steel production capacity by technology



Source: Ruijven et al. 2016

Figure 9: Direct and Indirect CO_2 Emissions from Steel and Cement production



Source: Ruijven et al. 2016

3.2.8 Wyns and Axelson 2016 The Final Frontier

Wyns and Axelson 2016 The Final Frontier – Decarbonising Europe's energy intensive industries, 64 pages

Table 25: Wyns and Axelson 2016, general information

Carried out by:	The Institute for European Studies, Vrije Universiteit Brussel (VUB); Tomas Wyns & Matilda Axelson

Commissioned by	Carbon Market Watch
Link:	http://www.ies.be/files/The_Final_Frontier_Wyns_Axelson_0.pdf
Range of emission reductions achieved	-80% (2050 vs. 1990)
Aim:	The study aims to identify options for deep greenhouse gas emission reductions by EU energy intensive industries which can enable emission reduction of -80% in 2050 compared to 1990 levels. It considers innovative process technologies along with business model and product innovations.
Sectoral coverage:	Direct emissions from chemical (petrochemicals, ammonia and fertilizer production), steel, cement sector
Geography:	EU
Time horizon:	1990-2050
Modelling approach:	For each sector, promising alternative emission reduction options for deeper reductions are qualitatively selected and their contribution is described. Subsequently the study analyses barriers to realize the full potential of those options and options to overcome the barriers. The study does not have a model to calculate total emission reductions resulting from the described technologies. However, the study mentions direct emission levels for all three sectors in 1990 gathered from EEA for the steel and the chemical sector and from GNR data for the cement sector. The reduction target is defined as -80% with the inclusion of defined technologies.
General Assumptions:	Mitigation options based only on current technologies are not sufficient to reach the targeted reductions Economic challenges might prevent the necessary investment in breakthrough technologies.
Other aspects	The study also introduces "The EU ETS Innovation Fund" which is the successor of NER 3000 and makes suggestions for its design.

3.2.8.1 Scenario description and main assumptions

There are no differentiated scenarios. The study analyses alternative technologies for deeper emission reductions to reach -80% reduction in 2050 in the steel, chemical and cement sector. For the steel sector this corresponds to a reduction of nearly 185 Mt CO_2 in annual emissions compared to 272 Mt CO_2 in 1990.

In the current status, BF-BOF accounts for the majority of steel production (61%) in the EU. The remaining share is produced via the EAF route. The EU steel industry is suffering from low steel prices due to overcapacity and international competition.

Even if the sector reached nearly -40% reduction in emissions compared to 1990 levels, further reductions are hard to achieve only with efficiency measures. The study represents three types of innovations for deeper emission reduction: process innovations, product innovations and business model transitions.

In **process innovations**, the study analyses four different technologies in the production of steel while in **product innovations** they mainly focus on improved material properties like improved stiffness and ductility at similar strength to reduce downstream emissions in industries that rely on steel like automotive or construction. **Business model innovations** give incentives for the implementation of new technologies.

3.2.8.2 Industry contribution in emission reduction in other industries

Product improvements can lead to a significant amount of emission reduction in downstream costumer sectors. For example, using high strength steel in car manufacturing can reduce the volume of steel needed. This is resulting in lighter automobiles which further reduce emissions by reducing the fuel consumption of the car.

Nanosteel is one of the steel producers producing high-strength steel by using nano-technological processes. General Motors Ventures are one of the lead shareholders of the company which shows the interest of downstream customers. This kind of acquisitions can also be done in European steel industry.

3.3 Pulp and paper Industry

3.3.1 CEPI 2011 Pulp and Paper low-carbon roadmap

CEPI 2011 2050 Roadmap to a low-carbon bio economy, 46 pages

Table 26: CEPI 2011, general information

Carried out and Commissioned by:	The Confederation of European Paper Industries (CEPI)
Link:	http://www.cepi.org/system/files/public/documents/publications/environment/2011/roadmap_final-20111110-00019-01-E.pdf
Range of emission reductions achieved	-75% (2050 vs. 1990)
Aim:	The study explores the potentials to reach 80% carbon emission reduction in the pulp and paper sector while still being competitive and meeting the future demand of the consumer. The study relates to the context of the 2050 low carbon roadmap of the EU. The study concludes that an 80% emission reduction in the forest fibre industry can only be reached by breakthrough technologies. The commercialization of those technologies requires policy support for industry to enable a successful transition and prevent carbon leakage.
Sectoral coverage:	Forest fibre industry – the pulp, paper and board and wood products sectors combined Direct as well as indirect emissions from electricity and transport are included, but separately shown.
Geography:	EU27
Time horizon:	1990 – 2050
Modelling approach:	Abatement options are individually discussed and quantified.
General Assumptions:	The study is based on the global action scenario with effective technology of the EU Commission's "A Roadmap for moving to a competitive low carbon economy in 2050" including the expected decarbonisation of electricity, carbon neutrality of biomass, availability of carbon capture and storage, and realization of energy efficiency targets. It is also in line with the IEA blue low growth scenario and the Eurelectric Power Choices scenario. To reach the maximum abatement, additional investment in breakthrough technologies is necessary.

Other aspects	Virgin fibre input into the graphic paper products is essential for the recycled fibre loop.

3.3.2 Scenario descriptions and main assumptions

In the study there are no different scenarios. The general assumptions which affect the entire EU are based on the assumptions in the global action scenario with effective technology from the EU low carbon roadmap.

Apart from the general assumptions, the study contains some industry specific assumptions.

- The ratio between recycled and virgin fibre for paper and board production is assumed to change from 50/50 to 60/40 in 2050 conditional on the recycled paper staying in Europe. High quality virgin fibres from printing and writing paper will decrease while recycled paper from hygiene products will increase.
- Since the paper quality will decrease, starch and other chemicals will be used to improve strength. Unusable recycled fibres will be used in bio energy production.
- genetically modified organisms (GMO) trees which are more resistant and need less water will not be in the agenda of EU due to the customer preferences and forest rotation periods
- The overall demand for wood will not decrease in spite of increasing availability of recycled paper. This is due to the expanded demand from bio-chemistry, biofuels and bio-energy
- Fibres from sources other than wood products are unlikely to completely replace woody fibres but can be mixed with woody fibres to reduce the costs.

With the assumptions from EU Roadmap, the emission reduction potential of specific reduction options is given below;

Direct emission reductions come from the following measures:

- Adoption of Best Available Technologies 10 Mt
- Fuel mix change 5 Mt
- Infrared dryers 1 Mt

Indirect emission reductions are distributed as follows:

- Transport 5 Mt
- Decarbonisation of Electricity 13 Mt

Breakthrough technologies to reduce heat demand in paper making, by reducing water use and improving drying processes, would lead to additional savings of 14 Mt (p.22).

In 1990 the sector is said to have had emissions of roughly 60 Mt CO_2 of which 40 Mt were direct emissions, 15 Mt indirect emissions from electricity purchased and 5 Mt transport emissions.

The reduction of direct emissions from 1990-2050 is estimated at -75% (from 40 Mt to 10 Mt) when all existing abatement options (abatement by -16 Mt) and breakthrough technologies (by 14 Mt) are adopted.

In its new short study "Investing in Europe for Industry Transformation", CEPI (2017) depicts largely similar emission reduction potentials.

3.3.3 Technology Overview

The CEPI roadmap includes the application of best available technologies such as recovery boilers, a change towards electricity based drying, and increased use of biomass. Furthermore, the study mentions as emerging technologies a lowering of the heat demand in paper machines' drying sections, layered sheet-forming, advanced fibrous fillers and highly selective fractionation processes. For pulp production, efficiency in refining and grinding for mechanical pulp production could be increased via pre-treatment of woodchips to reduce energy consumption.

The study further points to new products and services such as the production of nanocellulose, bio-composite materials, biofuels and bio-chemicals, black liquor gasification in pulp mills with an emerging thermochemical path for producing syngas, and the extraction of lignin from pulping liquor to replace fossil fuel materials in any sector.

Increased recycling and better sorting could free up more fibres for the sector and can also be used as an energy source. This would also avoid landfill emissions and improve resource efficiency.

The study also mentions the potential of integrated bio-refinery complexes (e.g. pulp and paper mills with waste management and incineration facilities).

A detailed technology overview is included in the annex.

Additional technologies mentioned in the study

Apart from the best available and emerging technologies mentioned above, the paper points to the need for breakthrough technologies to reach the desired reduction level of -80%. However the study does not give specific details about those technologies apart from mentioning CCS and BECCS.

The study further points to non-technological advancements in forest practices such as harvesting, sustainable forest practices etc., as well as within pulp and paper production such as increased use of fillers, coatings and other chemicals for enabling further energy saving potentials, and creating other value added products via modifying the properties of fibre.

The importance of transportation cost is mentioned separately. To neutralise the total transport emission of the wood industry, a biofuel equivalent of approximately 4 million tons of wood based biodiesel is needed. It is not mentioned whether this is feasible or not until 2050.

3.3.4 Industry contribution in emission reduction in other industries

- Wood-based construction materials: Substituting cement or steel with a cubic meter of wood results in average CO_2 savings of 1.1 tonnes.
- Lightweight paper for office applications could reduce resources needed.

3.4 Chemical Industry

3.4.1 CEFIC 2013 Chemistry future

CEFIC 2013 European chemistry for growth – Unlocking a competitive, low carbon and energy efficient future, 186 pages

Table 27: CEFIC 2013, general information

Carried out by:	Ecofys
Commissioned by	CEFIC
Link:	http://www.cefic.org/Documents/RESOURCES/Reports-and-Brochure/Energy-Roadmap-The%20Report-European-chemistry-for-growth.pdf
Range of emission	-31% to -71% (2050 vs. 1990)

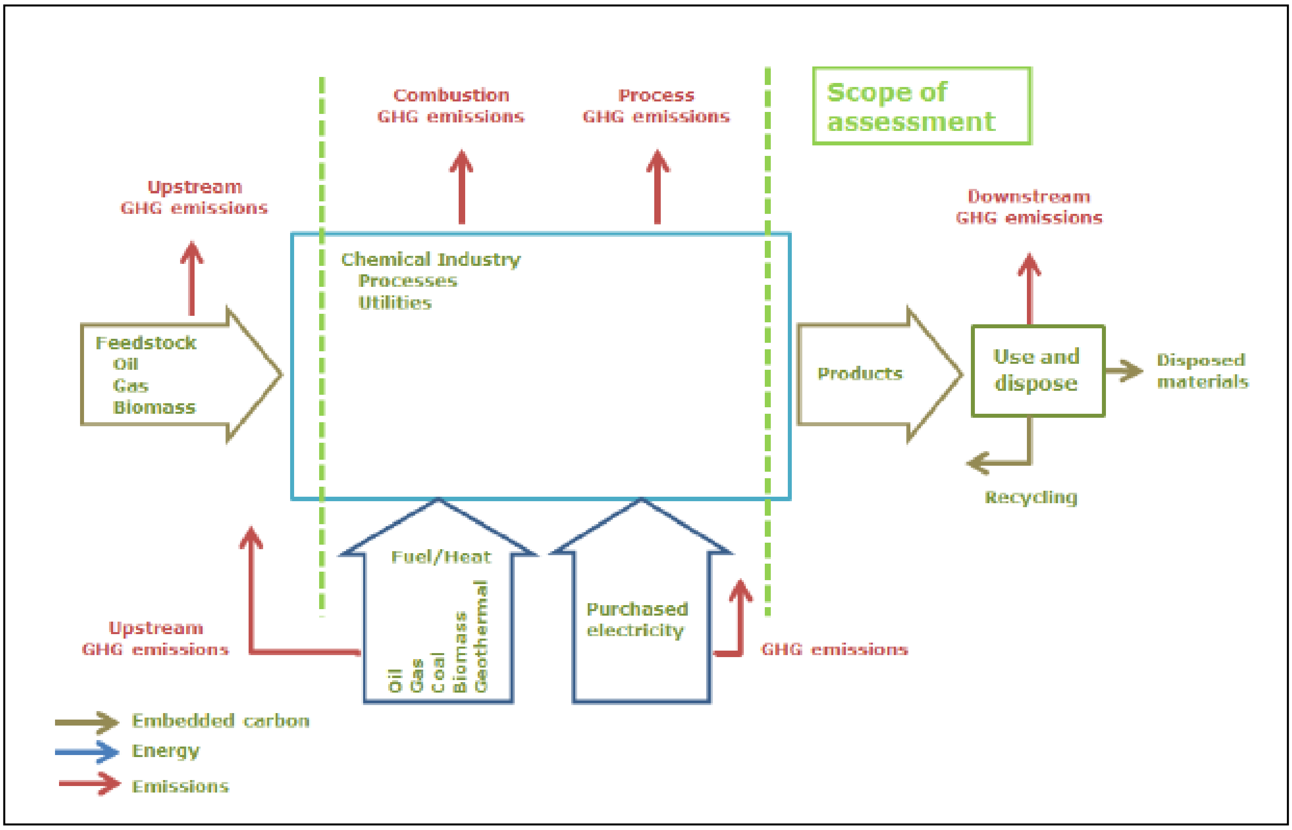
reductions achieved	
Aim:	The study aims at assessing the potential impact of existing and new technologies on energy efficiency and GHG emission levels up to 2050, as well as the competitive position of the European chemical industry. The study claims that a reduction of -15% to -25% by 2030 comparing to 2010 levels can be achieved by the chemical sector itself. Further substantial reductions until 2050 require the application of CCS. The study states that to reach the target level of EU Commission, global action is needed. The study claims that the chemical industry contributes to sustainable development, but for this to work a complete chemical value chain in Europe is needed. This is said to be seriously put at risk by isolated action by the EU which could cause carbon leakage and damage to the EU economy. European policy makers are called to support an innovation friendly environment for the chemical industry and enable it to compete on a global level playing field.
Sectoral coverage:	Chemical sector with five subsectors: Petrochemicals (including intermediates), Basic Inorganics, Polymers, Specialty Chemicals and Consumer Chemicals Direct and indirect emissions are covered as well as N_2O emissions.
Scope:	The roadmap investigates CO_2 emissions from the use of fossil fuels and N_2O emissions in the European (EU27) chemical industry and GHG emissions related to the production of purchased electricity and heat. An illustration of the scope can be found in Figure 10.
Geography:	EU27
Time horizon:	2010 - 2050
Modelling approach:	The study assesses the European chemical industry in 4 scenarios Continued Fragmentation; Global action is absent, -40% reduction compared to 1990 levels, Isolated Europe; Low global ambition -80% reduction in Europe Differentiated Global Action; global GHG emission reduction of approximately -50% between 1990 and 2050, -80% reduction in Europe Level Playing Field; global GHG emission reduction by -50% between 1990 and 2050 and uniform global carbon price The scenarios use different assumptions concerning: energy and climate policy environment in Europe and in the rest of the world outlook on the development of energy and feedstock prices speed of innovation The reductions in the different scenarios are estimated with an excel-based tool that carries out the following calculations: Projection of future demand for chemical products Deduction of EU production of chemical products for the sub-sectors Calculation of trade-ratio based on demand and production Modelling of stock of existing plants and new plants, combined with assumptions on energy efficiency and emission intensity. For cracker products, ammonia, chlorine, nitric acid a detailed analysis of energy efficiency and GHG abatement measures was carried out based on a profitability analysis. Calculation of energy consumption and GHG emissions based on plants used to produce the quantity of each product/subsector. Calculating overall results for the chemical industry by summing up the results for individual subsectors and products.
General Assumptions:	The Roadmap takes into account both CO_2 emissions from the use of fossil fuels and N_2O emissions which are the two most important GHG emitted by the chemical industry as well as indirect emissions from purchased electricity and heat. The base year for the calculations is 2010.

Other aspects	The study includes only few detailed numbers. Most information on abatement is in figures. The maximum abatement level is the minimum feasible emission level that can be achieved without replacing production and it can only be achieved in the level playing field scenario. Hence, even if the maximum abatement that could be achieved within Europe is higher, globally no reduction would be achieved because of production shifts. The study explicitly mentions that because of lacking data especially for cost, no marginal abatement cost curve for all options could be provided in the study.

3.4.1.1 Scenario description and main assumptions

The CEFIC study considers both direct and indirect as well as CO_2 and non-CO_2 emissions. Figure 10 depicts the scope of the assessment.

Figure 10: Scope of “Unlocking a competitive, low carbon and energy efficient future”



The study assesses the emission development of the European chemical industry in four scenarios that are aligned with the scenarios considered in the COM low carbon roadmap.

Continued Fragmentation; **Global** action is absent, the EU continues current policy, however with reduced ambition level

- Economy-wide -40% emission reduction, for industry -46% emission reduction target for 2050 compared to 1990 levels
- No global commitment to be in line with 2 °C target
- No actions beyond the current policies are undertaken
- No convergence in fossil fuel prices and high fossil fuel prices
- Existing ETS scope, declined free allocations for industry, no free allocations for the power sector in 2030-2050 period. No effective CO_2 price signal in the rest of the world
- Low innovation level in new technologies and no investment in breakthrough technologies

- EU Energy Roadmap's Current Policy Initiatives (CPI) scenario

Isolated Europe; Global action is absent, however high ambition level for EU

- Economy-wide -80% emission reduction and a similar reduction target for industry for 2050 compared to 1990 levels
- No global commitment to be in line with 2 °C target
- Current EU policies are implemented, as well as carbon pricing for all sectors of economy with no specific support measures for energy efficiency and renewable in the market where all energy sources can compete on a market basis
- Equal CO_2 prices from 2020 onwards for ETS and non-ETS sectors without free allocations while no effective CO_2 price signal exists in the rest of the world
- Medium but accelerated innovation level due to the high CO_2 prices
- High fossil fuel prices. The high price level of fossil fuels gives the incentive to reduce consumption and therefore, the carbon price needed to reduce emissions is lower than in the Differentiated Global Action scenario.

Differentiated Global Action; global GHG emission reduction target of approximately -50% between 1990 and 2050, -80% **reduction** in Europe

- Economy-wide -40% emission reduction, for industry -46% emission reduction target for 2050 compared to 1990 levels
- Global commitment to be in line with 2 °C target
- Current EU policies are implemented, as well as carbon pricing for all sectors of economy with no specific support measures for energy efficiency and renewable in the market where all energy sources can compete on market basis
- No convergence in fossil fuel prices. Limited use and price increase of fossil fuels
- Equal CO_2 prices from 2020 onwards for ETS and non-ETS sectors with declined free allocations for direct emissions and no free allocation for the power sector
- High level of innovation worldwide. High stimulus on the development of breakthrough technologies
- The ETS CO_2 prices are based on the "Diversified Supply" scenario in "The EU Energy Roadmap" (which would be: 2020: 25 €/t CO_2eq., 2030: 52 €/t CO_2eq., 2040: 95 €/t CO_2eq.,2050: 265 €/t CO_2eq.)[11]

Level Playing Field; global **GHG** emissions reduction target of -50% between 1990 and 2050 and uniform global carbon price

- Global 2 °C target and uniform CO_2 prices determine where abatement takes place, thus no differentiated target for the EU
- Global commitment to be in line with 2 °C target and fully linked trading system
- Current EU policies are implemented, as well as carbon pricing for all sectors of the economy with no specific support measures for energy efficiency and renewable in the market where all energy sources can compete on a market basis
- No convergence in fossil fuel prices, limited use and price increase of fossil fuels
- Equal CO_2 prices from 2020 onwards for ETS and non-ETS sectors without free allocations and a uniform global CO_2 price signal

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[11] See COM 2011c, COMMISSION STAFF WORKING PAPER, Impact Assessment, Accompanying the document Energy Roadmap 2050.

- High level of innovation worldwide. High stimulus on the development of breakthrough technologies

Table 28: CEFIC 2013 CO_2 and energy price assumptions

Parameter	Year	Continued Fragmentation		Isolated Europe		Differentiated Global Action		Level Playing Field	
CO_2 prices (€ '10)/t CO_2)	2010	15		15		15		15	
	2020	16		21		26		19	
	2030	33		44		54		37	
	2050	53		221		276		194	
Energy prices		w/o CO_2 cost	Incl. CO_2 costs	w/o CO_2 cost	Incl. CO_2 costs	w/o CO_2 cost	Incl. CO_2 costs	w/o CO_2 cost	Incl. CO_2 costs
Electricity (€ '10/GJ)	2010	21.9	23.1	21.9	23.1	21.9	23.1	21.9	23.1
	2020	27.2	28.2	28	29.2	28	29.4	28	29
	2030	28.2	29.9	35.1	36.7	25.3	26.8	34.2	35.6
	2050	27.7	29	37.6	37.6	26.2	26.2	35.4	35.4
Natural gas (€ '10/GJ)	2010	7.3	8.2	7.3	8.2	7.3	8.2	7.3	8.2
	2020	8.4	9.3	8.4	9.6	8.4	9.8	8.4	9.4
	2030	10.1	12	10.1	12.6	8.3	11.3	8.3	10.3
	2050	12.8	15.8	12.8	25.2	6.8	22.3	6.8	17.7
Oil (€ '10/GJ)	2010	11.9	13	11.9	13	11.9	13	11.9	13
	2020	12.4	13.5	12.4	13.9	11.8	13.7	11.8	13.2
	2030	14.6	17.1	14.6	17.9	11.1	15.1	11.1	13.8
	2050	17.4	21.3	17.4	33.6	10	30.2	10	24.2
Coal (€ '10/GJ)	2010	4.9	6.3	4.9	6.3	4.9	6.3	4.9	6.3
	2020	5.6	7.1	5.6	7.6	5.2	7.6	5.2	7
	2030	6.1	9.2	6.1	10.3	5.3	10.4	5.3	8.8
	2050	6.2	11.2	6.2	27.1	4.7	30.8	4.7	23
Biomass (€ '10/GJ)	2010	13.2				13.2			
	2020	14.3				14.3			
	2030	14.3				13.3			
	2050	13.3				12.3			

Parameter	Year	Continued Fragmentation	Isolated Europe	Differentiated Global Action	Level Playing Field
Geothermal (€ '10/GJ)	2010	10.0			
	2020	7.0			
	2030	5.6			
	2050	5.0			
Electricity emission factor (t CO_2/MWh)	2010	0.31	0.13		
	2020	0.22	0.2		
	2030	0.18	0.12		
	2050	0.09	0		

Table 29: CEFIC 2013 Fuel mix for heat generation

Year	Resource	Continued Fragmentation	Isolated Europe	Differentiated Global Action	Level Playing Field
2020	Coal	5%	5%	4%	4%
	Oil	8%	8%	8%	8%
	Natural gas	84%	83%	81%	84%
	Biomass	3%	4%	5%	4%
	Geothermal	0%	0%	2%	0%
2030	Coal	0%	0%	0%	0%
	Oil	5%	5%	5%	5%
	Natural gas	90%	88%	83%	86%
	Biomass	5%	5%	8%	6%
	Geothermal	0%	2%	4%	3%
2050	Coal	0%	0%	0%	0%
	Oil	5%	5%	5%	5%
	Natural gas	87%	78%	65%	71%
	Biomass	8%	12%	20%	16%
	Geothermal	0%	5%	10%	8%

3.4.1.2 Overview of scenario results

Table 30: CEFIC, overview of scenario results

Scenario	Emission levels (2050)*	Assumptions	Production & Implemented Technologies and related costs
Continued Fragmentation	253.8 Mt CO_2	No global action 46% reduction target for EU Industry High fossil fuel prices Low CO_2 prices Low difference difference in CO_2 price with the rest of the world	Negative impact on production Negative to neutral net trade ration
Isolated Europe	94 Mt CO_2	No global action High fossil fuel prices 20% lower CO_2 prices compared to “Differentiated Global Action”, high difference in CO_2 price to rest of world No free allocations 2020 onwards	Negative impact on production Negative net trade ration
Differentiated Global Action	94 Mt CO_2	Global action High CO_2 prices, rising but medium CO_2 price difference to rest of world No specific measures for renewable energies, equal rights in energy market Limited fossil fuel price increase	Negative impact on production Negative to neutral net trade ration
Level Playing Field	200 Mt CO_2	Uniform CO_2 prices Limited fossil fuel price increase	Full integrated value chain remains in Europe Positive net trade ratio

3.4.1.3 Technology Overview

The emission reduction potentials in the chemical industry are analysed in four different groups of options. Due to the emission intensity of the production of ammonia, cracker products, chlorine and nitric acid, apart from the general reduction option groups, the reduction options for those chemicals are discussed separately. Emission options from the purchased electricity are not detailed as part of the study since it is largely outside the control of the chemical industry.

The study includes several options of a changed feedstock that is bio-based chemicals and feedstock recycling. There are also several efficiency measures presented such as process intensification and heat recovery measures. The detailed technology overview is presented in the annex.

3.4.1.4 Industry contribution in emission reduction in other industries

The study calculates the contribution of current chemical solutions to emission reduction in different other industries compared to the next best non-chemical solution. They include insulation, wind power, lighting, packaging, automotive weight, marine antifouling, solar power, fertilizer and crop protection industries. The total contribution is estimated as 1,555 Mt CO_2. net avoided emissions if chemical products are being used in those applications.

3.4.2 Wyns and Axelson (2016) The Final Frontier

Wyns and Axelson (2016) The Final Frontier – Decarbonising Europe’s energy intensive industries, 64 pages. For general information on the study please refer to the study profile in section 3.2.8

3.4.2.1 Scenario description and main assumptions

In the study, there are no distinguished scenarios. Instead, alternative technologies which can enable -80% or more emission reduction are described. For the chemical sectors, this corresponds to a reduction of more than 260 Mt CO_2eq. compared to 325 Mt CO_2eq. in 1990. Due to the complexity of the sector, the study focuses on the subsectors petrochemicals (polymers and plastic in particular) and ammonia production.

According to the study, the chemical industry's low hanging fruit reduction potentials and efficiency measures are nearly exploited. Hence, for deeper emission reduction, breakthrough technologies, new products and feedstocks with innovations in business models are needed.

Petrochemicals

The study considers two main reduction options in the petrochemical industry: replacement of fossil fuel based feedstock with biomass-based alternatives and enhanced recycling to reduce production of important petrochemicals. The details for the technologies are given in the Technology overview.

According to the study, in total € 3.7 billion have been invested in bio-based innovations to replace fossil fuel inputs in the EU between 2014-2020. € 975 million relate to a Horizon 2020 initiative, others are private investment. The aim of those efforts is to replace at least 30% of petroleum based chemicals with bio-based and bio-degradable products which on average reduce **emissions by 50% compared to fossil alternatives**.

Capturing sufficient biomass/forest residues for the above purpose is said to be possible until 2020. However it may imply that those residues are not used for production of energy or bio-based fuels.

Recycling of plastic products also represents a significant potential in EU. If current and proposed EU legislations are applied fully, recycling leads to a reduction of **18 Mt CO_2eq. in 2025.**

Ammonia and fertilizer production

Ammonia production represents nearly 20% of GHG emissions from the Chemical industry in thr EU. The maximum emission reduction would be -25% in 2050 compared to today's level, if all the production facilities are upgraded to the current state of the art production efficiency. To achieve at least -80% reduction, technological innovations and effective business models are needed such as the electrochemical production of ammonia, the use of bio-based waste or business model revolutions in the fertilizer industry.

3.4.2.2 Industry contribution in emission reduction in other industries

N/A

3.5 Non-metallic Mineral Industry

3.5.1 Cement Industry Technology Overview

The main ingredient of cement is clinker. It is produced by decarbonization and mineralization of limestone in high temperatures. Therefore, this process is highly energy and carbon intensive.

The studies on emission reduction in the cement industry focus on similar reduction technologies which mainly target materials which can be a substitution for clinker and changes in the fuel mix. An overview is provided in the technology tables' section in section 4.4. The studies which have included a specific technology in their analyses are mentioned in the last column. If there is specific information given which is only mentioned in one study, the abbreviation of that study can be found next to the information.

Additional to the technologies within production, emission reductions from increased transport efficiency are mentioned briefly in CEMBUREAU (2013). Increased use of inland waterways and rail networks as well as building new plants close to the transportation hubs are assumed to achieve a decrease of -50% of the emissions caused by transportation in the sector today until 2050.

CEMBUREAU (2013) also mentions some technologies which can be implemented after the carbon being captured such as Carbon Capture Utilisation Carbon Capture & Storage and Carbon Capture Valorisation. Utilization and valorisation of the captured carbon is preferred, however due to the uncertainties in the amount that can be utilized, the storage option is also taken into consideration. The study does not give detailed information about the usage.

In addition to the already mentioned technologies the following low-carbon cement options are discussed in IEA (2009):

- **Novacem:** based on magnesium silicates (MgO) rather than limestone (calcium carbonate). By using a low carbon low temperature process, MgO is converted into magnesium oxides. Mineral additives are used to enhance strength and accelerate carbon absorption.
- **Calera:** mixture of magnesium and calcium silicates. In the production process, waste heat from flue gas is brought into contact with sea water, brackish water or brine to absorb CO_2.
- **Calix:** Production of cement by rapid calcination of dolomitic rock in superheated steam capturing the CO_2 by filters.
- **Geopolymer cement:** Production of alkali activated cement from waste material from steel (slag), power (fly ash, bottom ash) and concrete production. This process is commercialized in small facilities.

3.5.2 CEMBUREAU 2013 Cement low-carbon roadmap

Cembureau 2013: The role of Cement in the 2050 low carbon economy, 64 pages

Table 31: CEMBUREAU 2013, general information

Carried out and Commissioned by:	The European Cement Association
Link:	http://lowcarboneconomy.cembureau.eu/uploads/Modules/MCMedias/1380546575335/cembureau---full-report.pdf
Range of emission reductions achieved	-29 to -79% (2050 vs. 1990) direct emissions only -32 to -80% (2050 vs. 1990) direct and indirect emissions
Aim:	The study sheds light on CO_2 emission reduction potentials in the cement industry with the current technology and gives an outlook on what could be achieved by 2050. The study states that by parallel implementation of available technologies an emission reduction (direct + indirect) of -32% (2050 compared to 1990 emission level) can be achieved. With breakthrough technologies like CCS a reduction of -80% can be reached but this requires support of policy makers. The study points to effects beyond the cement sector and underlines that the industry could contribute more to the low carbon economy than emission reduction in cement production e.g. low carbon concrete or energy efficient buildings.
Sectoral coverage:	Cement The study considers process emissions, direct emissions from fuel combustion and indirect emissions from electricity use and emissions from transportation of materials.
Geography:	EU27
Time horizon:	1990-2050
Modelling approach:	The abatement potential quantified from the technologies described under Technology Overview. The parallel routes are: Resource efficiency: alternative fuels (use of biomass), raw material substitution (avoiding limestone), clinker substitution, novel cements, transport efficiency (e.g. modal shift). Energy efficiency: electrical energy efficiency (replace old plants, use of modern clinker cooler technology), thermal energy efficiency Carbon sequestration and reuse, biological carbon capture Product efficiency: low carbon concrete Downstream: Smart building and infrastructure development, recycling concrete, recarbonation, sustainable construction
General Assumptions:	The production level of cement in 2050 is assumed to be the same as in 1990. The power sector is assumed to be fully decarbonised in 2050. Efficiency of transportation is assumed to increase by 50%. Plant capacity is assumed to double to 5000 t of clinker per day. The fuel mix is assumed to be 60% alternative fuels (40% of which biomass), 30% coal and 10% pet coke. For non-kiln fuels (e.g. for drying of raw materials, vehicles and space heating, a -30% reduction in emissions has been assumed. Cement manufactured in 2050 is assumed to contain 70% clinker. Novel cements are expected to have 50% lower CO_2 emissions than common cements and are assumed to make up 5% of total cement production in 2050. Breakthrough technologies: 85% of total clinker production is assumed to be equipped with e.g. carbon capture and storage technology.
Other aspects	Production 2011: 191 Mt of cement, 140 Mt clinker 1990 emission level: 170 Mt CO_2 (157.3 Mt CO_2 direct emission)

3.5.2.1 Scenario descriptions and main assumptions

In this study, abatement potential from the industry resulting from the application of conventional and breakthrough technologies is presented. The details of the technologies are presented in section 3.5.1 Cement Industry Technology Overview.

Best available technologies are projected to achieve a -32% reduction in sectoral emissions in 2050 compared to 1990 and the -80% reduction target can only be achieved with breakthrough technologies. With respect to only direct emissions, this corresponds to -29% (diffusion of BATs) and -79% (with breakthrough technologies).

The reduction of direct emissions is achieved by an increase in kiln efficiency and improvements in the fuel mix (-34 Mt CO_2eq.) as well as clinker substitution and use of novel cements (-11 Mt CO_2eq.). Indirect emission reductions are achieved with increased transport efficiency (-2 Mt CO_2eq.) and a decarbonisation of electricity (-10 Mt CO_2eq.). Breakthrough technologies would lead to additional emission reductions of -79 Mt CO_2eq.

3.5.2.2 Industry contribution to emission reductions in other industries

Low carbon concrete

Using locally sourced aggregates and recycled materials from constructions and demolitions in a radius of 40 km helps cutting transport emissions. Furthermore, the use of high performance cement instead of conventional cement can reduce the cement content in concrete to a certain extent. The reduction is limited by the quality of cement standards.

Admixtures are added chemicals in concrete to change its plastic or hardened state. By optimizing the mixture, emissions, water usage and energy consumption can be reduced. Increased fluidity and reduced permeability as well as improved appearance help to increase the life time of the concrete. Additionally, the admixture can be produced from bio-materials like corn or wood or from by-products from the paper and pulp industry which reduces the carbon footprint.

Sustainable use of concrete

Energy consumption of buildings made out of concrete can be significantly reduced by using best available technologies. Also some part of the buildings can be re-used in another construction or during deconstruction.

Crashed concrete can be used as aggregate in the production of concrete or backfilling for other applications. To recycle and re-use the concrete, it is necessary to consider this during the design phase. Then during demolition or renovation, the waste concrete can be re-used. The most common usage of crushed concrete is in road constructions. For an optimized utilization of hardened concrete from waste the separation technology should be improved.

The surface of concrete absorbs CO_2 when it is exposed to air and moisture. This is called recarbonation. Recarbonation of concrete can be utilized when it is crushed prior to re-use. By leaving the crushed concrete exposed to air, up to 25% of the emitted CO_2 during the production can be absorbed. However to obtain the maximum effect, it should be left in open air for several months which requires a new system design for construction waste management.

The sustainable usage of concrete in constructions can also create a difference in energy consumption of buildings. Concrete roads reduce the fuel consumption of vehicles and also due to its high albedo; it reduces the need of street lightning and the heat island effect in cities.

3.5.3 IEA 2009 Cement Technology Roadmap

IEA 2009 Cement Technology Roadmap 2009, 36 pages

Table 32: IEA 2009, general information

Carried out by:	International Energy Agency (IEA), World Business Council for Sustainable Development (WBCSD)
Commissioned by	G8 leaders in Hokkaido
Link:	http://www.nocarbonnation.net/docs/roadmaps/Cement.pdf, www.wbcsdcement.org/technology
Range of emission reductions achieved	n.a.
Aim:	The study aims to define the key technological reduction levers and give policy recommendations to reach a -50% emission reduction in 2050 compared to 2006. The study states that political and economic support and technological development are required to halve the global energy related GHG emissions in 2050 compared to 2006. It mentions that some technologies face regional limitations.
Sectoral coverage:	Cement
Geography:	Global
Time horizon:	2006 - 2050
Modeling approach:	The roadmap is based on a model for the cement industry in the context of IEA's BLUE scenarios, which examine the implications of an overall policy objective to halve global energy-related CO_2 emission intensity in cement sector in 2050 compared to the 2006 level
Assumptions:	
Other aspects	The study does not mention 1990 emission levels. Global production level in 2006 is 2.55 Billion tonnes which shows an increase of 54% compared to 2000 while the absolute CO_2 emissions increased by 42% reaching 1.88 Gt in 2006. The technology options for emission reduction are outlined in 38 technology papers. In this study only a summary of those technologies are given. The given technology options cannot be added up to obtain a total amount of reduction potential due to the influence of one on another. Global cement industry fuel mix: 90% fossil fuel, 7% alternative fuel, 3% Biomass

3.5.3.1 Scenario descriptions and main assumptions

Process indicators

In the study certain indicators have been set to track the progress in cement industry. These indicators are given below.

Table 33: IEA 2009 process indicators

	2012	2020	2025	2030	2050
specific thermal energy consumption in GJ/tonne clinker	3.9	3.5-3.7	3.4-3.6	3.3-3.4	3.2
Share of alternative fuel & biomass use	5-10%	12-15%	15-20%	23-24%	37%
Clinker to cement ratio	77%	74%	73.5%	73%	71%
CCS no. of pilot plants	2				
CCS no. of demo plants operating		6			
CCS no. of commercial plants operating			10-15	50-70	200-400
CCS: Mt of CO_2 stored	0.1	5-10	20-35	100-160	490-920
Emission intensity: Tonne CO_2 emissions per tonne cement	0.75	0.62	0.59	0.56	0.42

Table 34: IEA 2009 Emission factors

Coal	4.4 $MtCO_2$ / mtoe
Oil	3.2 $MtCO_2$ / mtoe
Gas	2.34 $MtCO_2$ / mtoe
Alternative Fuel Usage (average)	1.85 $MtCO_2$ / mtoe
CCS Process	0.54 $MtCO_2$ / t Clinker

Table 35: IEA 2009 Global indices and global volume in 2006

% Clinker	79
% alternative fuels (including biomass)	3
Energy consumption (Gj/t Clinker)	4.2
Emission intensity (t CO_2 /t cement)	800
Production volume (Mt)	2559
CO_2 emission (Mt)	2047

3.5.3.2 Overview of scenario results

The study presents results from the IEA's BLUE scenarios, featuring four different scenarios: two baseline and two roadmap scenarios. The baseline scenarios represent a forecast if only the current policies are implemented worldwide. The roadmap scenarios indicate the results assuming the technologies in the roadmap are implemented in order to halve the emissions compared to the BLUE scenario. Both baseline and roadmap scenarios take into account high and low cement demand.

Table 36: IEA 2009 overview of scenario results

Scenario	Emission levels (2050)	Assumptions	Production & Implemented Technologies
Baseline with high demand	2,796 Mt CO_2	High demand of cement No additional reduction effort	Production: 4,397 Mt Cement
Baseline with low demand	2,337 Mt CO_2	Low demand of cement No additional reduction effort	Production: 3,657 Mt Cement
Roadmap with high demand	1,548 Mt CO_2 with CCS 2,521 Mt CO_2 without CCS	High demand of cement Technologies implemented in line with indicators	Production: 4,397 Mt Cement Cost of the implementation is between $520 – $843 Billion
Roadmap with low demand	1,558 Mt CO_2 with CCS 2,052 Mt CO_2 without CCS	Low demand of cement Technologies implemented in line with indicators	Production: 3,657 Mt Cement Cost of the implementation is between $354 – $572 Billion

3.5.4 CS 2014 Cement report

Climate Strategies 2014 Carbon Control and Competitiveness Post 2020: The Cement Report, 55 Pages

Table 37: CS 2014, general information

Carried out and:	Climate Strategies (output of Energy Intensive Industries project)
Commissioned by:	Ministries in Germany, Netherlands, France, UK and by Tata Steel and Heidelberg Cement
Link:	http://climatestrategies.org/wp-content/uploads/2014/08/CS-20140221-EII-cement-report.pdf
Range of emission reductions achieved	-15% to 95% (2050 vs. 1990) (based on results from other studies)
Aim:	This report assesses how production and emission volumes, energy and CO_2 efficiency and competitiveness of companies in the Energy Intensive Industries have evolved prior and during the European Union Emissions Trading System (EU ETS). From that historical information, the study explores what is needed to unlock the further mitigation potentials. The study does not provide a roadmap. It rather represents the results of several studies and supports it by interviews with executives from the industry in terms of reforms in the EU ETS and other policy framework suggestions.
Sectoral coverage:	Cement
Geography:	EU
Time horizon:	Not Specified
Modelling approach:	In the study, information from different sources such as the WBCSD – CSI Getting the Numbers Right database, the EUTL, Eurostat, UN Comtrade trade flow data and company annual financial reports are collected and analysed. Additionally some interviews are conducted with executives from cement industry.
Assumptions:	Bio-mass or sustainably grown fuel is considered as carbon neutral

Other aspects	The study takes the industry as a whole and studies it from past to future from every angle taking the EU ETS system as a focus point in order to give accurate policy framework suggestions. It also analyses the possible mitigation options. The process emissions are given with roughly 530 kg CO_2/t clinker and fuel emission between 220 kg CO_2/t clinker and 500 kg CO_2/t clinker Indirect emissions from consumption of electricity (around 110 kWh/t cement) and the emissions from transportation are responsible for 5% of production emissions.

3.5.4.1 Scenario descriptions and main assumptions

The study does not provide a scenario or quantitative results.

3.5.4.2 Overview of emission reduction levers of cited studies

The study does not contain original modelling work but collects and condenses information from other studies. The following figure taken from the study depicts the main emission reduction levers within the cement sector to achieve a reduction of -80% by 2050 compared to 1990.

Figure 11: Different emission reduction levers within the cement industry

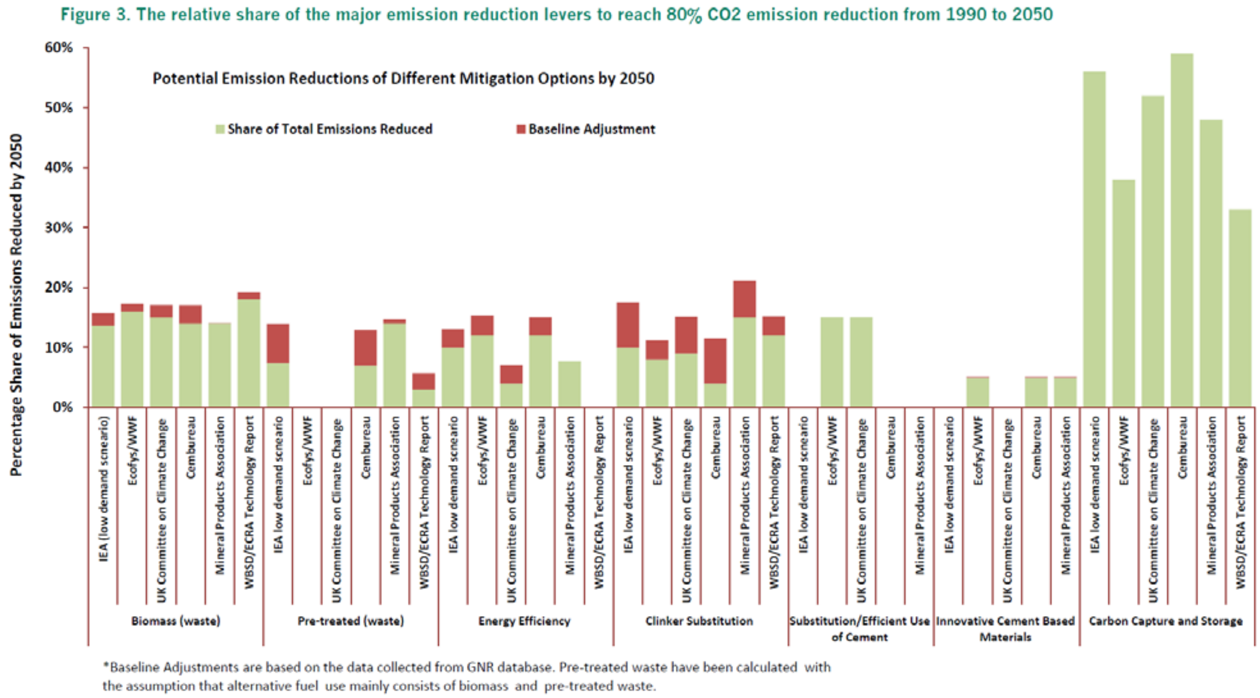


Figure 3. The relative share of the major emission reduction levers to reach 80% CO2 emission reduction from 1990 to 2050

*Baseline Adjustments are based on the data collected from GNR database. Pre-treated waste have been calculated with the assumption that alternative fuel use mainly consists of biomass and pre-treated waste.

Source: Neuhoff et al 2014 (Final Report Carbon Control and Competitiveness Post 2020: The Cement Report)

3.5.4.3 Industry contribution in emission reduction in other industries

Effective cement use in related industries can also lead to emission reductions.

- The use of concrete can be reduced by using wood-concrete composites in bridge constructions. This replacement can save 50% of concrete and 20% of steel required in the construction.
- Some of the building components in residential or commercial building constructions such as frames, inner and outer walls and floors can be built from wood and still have the same functions as concrete.

However those options are highly dependent on availability of materials, cost, cultural aspects and the building regulations.

Better planning and coordination between structural engineers and architects in construction during design and implementation can reduce material consumption.

3.5.5 Van Ruijven et al. 2016 Long-term projections for global steel and cement industries

Van Ruijven et al. 2016 Long-term model-based projections of energy use and CO_2 emissions from the global steel and cement industries. Resources, Conservation and Recycling 112 (2016) 15–36, 22 Pages. For the general overview see section 3.2.7.

Portland cement is used as reference. The share of clinker in cement is assumed to decrease linearly down to 65% in 2050 with carbon prices between 27 $/t CO_2 and 270 $/t CO_2 (see van Ruijven et al. 2016, p.22). Global emissions in the cement sector in 2010 are 3,050 Mt CO_2 (see van Ruijven et al. 2016, p.27).

3.5.5.1 Overview of scenario results

In the baseline scenario, the standard route remains dominant (nearly 90% of production capacity) in 2050. Efficient capacity has a share of 10-15%.

At a CO_2-price starting in 2020 at 20 $/t CO_2, in the year 2050 roughly 75% of the capacity uses on-site CCS. Less than 5% remain standard installations, and the rest is efficient installations. Higher CO_2-prices increase the share of on-site CCS to nearly 100% at a 2020 price of 100 $/t CO_2. When CCS is excluded, standard installations retain a slightly higher share, but the dominant technology is installations with improved efficiency.

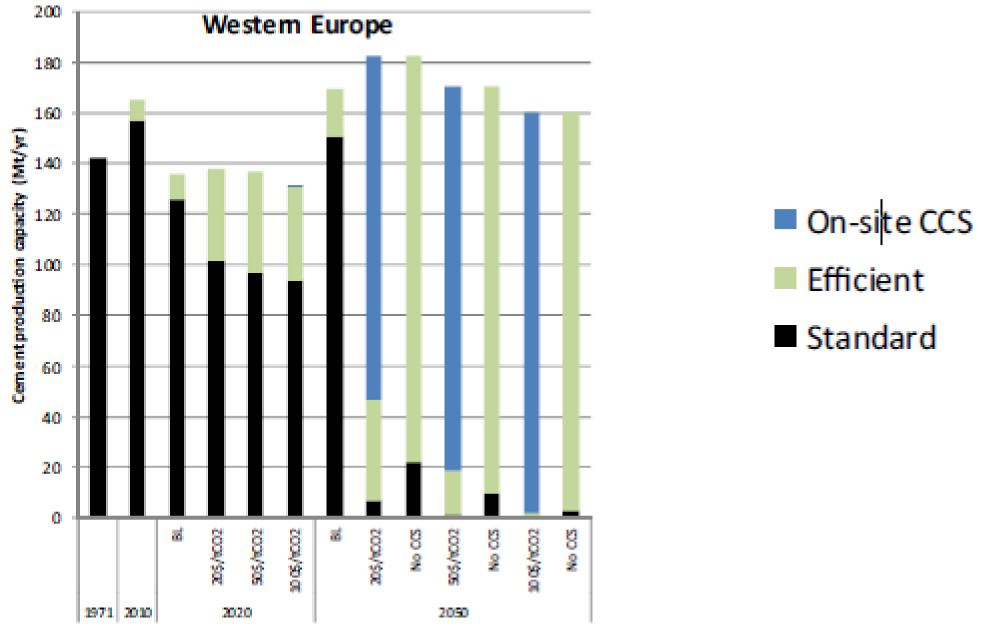
The table below gives some more information on the scenarios.

Table 38: Van Ruijven et al. 2016 overview of scenario results, energy-related emissions

Scenario	Emission levels (2050)/change compared to 2010)	Assumptions	Production & Implemented Technologies
Baseline	**Globally;** 2,900 Mt CO_2, -5% to 2010 **US;** 34 MtCO_2, -3% to 2010 **Western EU;** 55 MtCO_2, -37% to 2010 **China;** 630 MtCO_2, -55% to 2010 **India;** 470 MtCO_2, +224% to 2010	No further policies regarding emission reduction	Global Production increases from about 2,630 Mt in 2010 to 3,180 Mt in 2050. Some improvements are applied in the standard clinker production process (nearly 90% standard, 10-15% efficient capacity) Coal domination in the fuel mix
20$ / tCO_2	**Globally without CCS**; 2,030 MtCO_2, -33% to 2010 **Globally with CCS**; 750 MtCO_2, -71% to 2010	A carbon tax of 20$ / tCO_2 is introduced globally starting in 2020 with an annual increase of 4% ($65 in 2050)	75% of the capacity uses on-site CCS, 5% standard production process, 95% efficient installations
50$ / tCO_2	Between 20$ and 100$ scenarios	A carbon tax of 50$ / tCO_2 is introduced globally starting in 2020 with an annual increase of 4% ($162 in 2050) Fully decarbonized power sector	n.a

Scenario	Emission levels (2050)/change compared to 2010)	Assumptions	Production & Implemented Technologies
100$ / tCO_2	**Globally without CCS**; 1,740 $MtCO_2$, -43% to 2010 **Globally with CCS**; 580 $MtCO_2$, -81% to 2010	A carbon tax of 50$ / tCO_2 is introduced globally starting in 2020 with an annual increase of 4% ($324 in 2050) Fully decarbonized power sector	100% on-site CCS if available, efficient technologies are dominating production

Figure 12: **Cement production capacity by technology**



Source: Ruijven et al. 2016

3.5.6 Wyns and Axelson 2016 The Final Frontier

Wyns and Axelson 2016 The Final Frontier – Decarbonising Europe's energy intensive industries, 64 pages. For general information on the study please refer to section 3.2.8.

3.5.6.1 Scenario description and main assumptions

The study analyses alternative enabling technologies to reach -80% emission reductions in 2050 compared to 164 Mt CO_2eq. in 1990. It does not follow a scenario approach.

In the EU, cement is currently produced from four different routes: dry, semi-dry, semi-wet and wet kiln processes. The latter two represent only 10% of the production and are being gradually phased out due to their low energy efficiency. While energy efficiency measures are being applied, especially to new capacities, the sector still needs different approaches to reach the reduction target of -80%. The study analyses three of those approaches: Process innovations, clinker substitution and downstream demand reduction.

In **process innovations**, carbon capture and storage and limestone reduction through electrolysis technologies are analysed while in **clinker substitution** the focus is on alternative materials to replace clinker. More information can be found in the technology tables. In **downstream innovations**, innovative technologies to increase material and resource efficiency in the application of cement are discussed. This is described in the following section (3.5.6.2).

3.5.6.2 Industry contribution in emission reduction in other industries

Concrete typically needs 10-15% cement in volume to be produced. Nanotechnology can help to reduce that share. For example, nano-silica in concrete can lead to higher strength with lesser porosity. Although further research is needed on the state and dispersion of nanosilica in concrete, major benefits are expected from nanotechnology.

In the design stage of infrastructure and buildings, using advanced tools and training in architecture and civil engineering can help to use materials like concrete in a more efficient way maintaining the same or increased strength and resilience. 3D printing is one of the advanced tools in construction for that purpose.

3.5.7 Ceramie-Unie 2013 Pacing the way to 2050

Ceramie-Unie 2013 Pacing the way to 2050, 64 pages

Table 39: Ceramie-Unie 2013, general information

Carried out and Commissioned by:	Cerame-Unie
Link:	http://cerameunie.eu/topics/cerame-unie-sectors/cerame-unie/ceramic-industry-roadmap-paving-the-way-to-2050/?media=4249&f=Ceramic%20Roadmap%20to%202050%20EN.pdf
Range of emission reductions achieved	-50% to -77% (2050 vs. 1990)
Aim:	To point out the possible contribution of ceramics industry on the path to low carbon future in production and also the application of ceramics
Sectoral coverage:	Ceramics Real emission data from the bricks, roof tiles, wall and floor tiles and refractories sectors which together comprise approximately 90% of the entire ceramic sector's emissions. Both direct emission from process emission and fuel combustion, and indirect emissions from purchased electricity are included.
Geography:	EU27
Time horizon:	1990-2050
Modelling approach:	The reduction potential of current and some identified future technologies are analysed through real emission data
General Assumptions:	Constant level of production between 2010 and 2050 with a similar product mix and near-full kiln load Process emissions are unavoidable to create durable ceramics in the absence of carbon capture technologies. Syngas and bio-gas are assumed to have zero emission
Other aspects	Around 25% of production is exported from the EU27 which results in a positive trade balance. Annual production value is 28 Billion € in 2010. Energy mix is around 85% natural gas and 15% electricity. Diesel, LPG, coal or coke are only used when gas is not available.

	The ceramic industry represents 0.5% of total EU ETS emissions due to the fact that more than 75% of ETS ceramic installations are considered under the small emitter class with more than 75 t/day and emission of less than 25 kt CO_2/year. In 2011, the industry emitted 19 Mt CO_2 resulting to 66% from fuel combustion, 18% from purchased electricity and 16% from process emissions.

3.5.7.1 Scenario descriptions and main assumptions

In the study, two different scenarios are analysed. In both scenarios, four different reduction levers such as CCS, other breakthrough technologies, available technologies and syngas/biogas are taken into account. In the second scenario, additionally the effect of electrification of half of the existing kilns in between 2030 and 2050 is analysed. According to the study, this second scenario is an infeasible scenario due to the extremely high cost of conversion of the kilns. It would cause European manufacturers to lose its competitiveness in the international market.

3.5.7.2 Overview of scenario results

Table 40: Ceramie-Unie 2013 overview of scenario results

Scenario	Emission levels (2050)	Assumptions	Production & Implemented Technologies
Scenario without electrification of kilns	65% emission reduction compared to 1990 levels	No electrification of kilns	Constant level of production between 2010-2050 CCS and Other Breakthrough technologies Available technologies, Syngas/biogas
Scenario with electrification of kilns	78% emission reduction compared to 1990 levels	Electrification of half of the kilns	Constant level of production between 2010-2050 CCS and Other Breakthrough technologies Available technologies, Syngas/biogas Electrification of half of the kilns

The second scenario is considered infeasible scenario due to the extremely high cost of converting the kilns. Ceramie-Unie (2013) calculated the capital cost as 90 Billion €/year and up to 40 Billion € for writing off the plants before their life time and loss in sales during the modification period.

3.5.7.3 Technology Overview

The study differentiates the possible emission reduction technologies and applications according to the source of the emissions. The measures are electrification of kilns, improved thermal efficiency and heat recovery. Furthermore, alternative fuels and CCS are discussed. The technology overview is presented in the annex.

There are further technologies and their status mentioned in the study without further detail:

- Low temperature heat recovery from kiln exhaust – R&D
- Clay/raw material preconditioning – Pilot
- Process optimization – currently available and pilot applications
- Energy management - currently available, pilot and under research applications
- Raw material formulation changes for more efficient firing - currently available, pilot and under research applications

3.5.7.4 Industry contribution in emission reduction in other industries

Recycling: Bricks can be crushed into brick chips to be used for landscaping or raw material for other products. Building and demolition waste are used in road construction as a secondary aggregate.

Housing: In high thermal energy efficient innovative buildings, integrated insulation clay block envelopes ensure significant energy savings as well as the cool-roofs built from bright roof tiles that provide cooler houses in summer without the need for energy intensive cooling systems.

Shaping techniques based on the continuous compaction of recycled powders are also representing innovative low-carbon solutions.

Industrial applications: Finer abrasives and superabrasives enable precision in grinding and help to increase process efficiency particularly in aerospace, automotive and defence industries. Also ceramics in energy generation and distribution plays a big role to reduce emissions.

High-tech solutions: nano-engineered ceramics would be an important element for next generation capacitors to be used in conventional energy storages and intermittent sources such as wind and solar. They also might play a role in more energy efficient electric vehicles and other devices. High-tech ceramics for highly-efficient solid oxide fuel cells are in the R&D phase. They are already being used and also under development for better solutions for water filters, non-toxic coatings and many different solutions in health, electronics and other technologies.

3.5.8 ECOFYS 2014 Lime low carbon roadmap

ECOFYS 2014 A Competitive and Efficient Lime Industry, 61 pages

Table 41: ECOFYS 2014, Lime roadmap general information

Carried out by:	The European Cement Association
Commissioned by:	EuLA - The European Lime Association
Link:	http://www.eula.eu/documents/competitive-and-efficient-lime-industry-cornerstone-sustainable-europe-lime-roadmap-1
Range of emission reductions achieved	-31% (2050 vs. 2010)
Aim:	The study assesses emission reduction possibilities for the European Lime industry
Sectoral coverage:	Lime
Scope:	The scope of the roadmap includes scope 1 emissions (direct emissions at the site of the lime plants) and scope 2 emissions (indirect emissions related to the generation of purchased electricity). It covers only non-captive lime which is the lime that is sold on the market. Captive lime which is produced for the own use is not covered. Analysed lime types are quicklime, dolime and sintered dolime. Major CO_2 emissions result from the kilns. Emissions from other processes (around 2.2% of the total emissions) are not included to the calculations.
Geography:	EU28
Time horizon:	2010-2050
Modelling approach:	The roadmap has been developed by workshops with the actors in the industry. The evidence base gathered from the industry is supported by the data provided by the European Lime Association (EuLA).

General Assumptions:	71% decarbonization of power industry (in line with EU Commission Energy Roadmap scenario) is assumed for 2050 If the lime sector is not protected from unilateral EU climate policies it might suffer from high carbon prices. The carbon prices will be reflected to the consumer which will have a negative effect on EU demand of lime produced in EU.
Other aspects	Fuel mix in 2010 in the industry: Fossil solid fuels (51%), Natural Gas (34%), Waste (8%), Oil (5%), Biomass (2%) Electricity consumption of the industry is around 70 kWh/tonne Lime and the emission factor used in indirect emission calculations is 0.465 tonne CO_2/MWh CO_2 emission sources and their share are: Process emissions (68%), Fuel related emissions (30%), Electricity emission (2%) Average fuel consumption in 2010 was 4.25 GJ/tonne quicklime. The majority of the energy consumption in lime production is the heat required during calcination step. Currently, in Europe, 80% of lime is produced in vertical kilns

3.5.8.1 Scenario descriptions and main assumptions

The study analyses the possible abatement only in fuel emissions. There are no differentiated scenarios related to different parameters. In conclusion they represent two theoretical reduction potentials in addition to efficiency improvements in current processes.

- Switching all fossil solid fuel to natural gas until 2030
- A full decarbonization of the fuel mix until 2050

According to the paper, the only way to reduce process emissions, which account for 68% of total emissions, is carbon capture. All the other improvements and technological advancements target only fuel emissions. The effect of carbon capture is yet unknown. Therefore the maximum abatement potential cannot be predicted. The study only indicates the carbon emission reduction potential of the lime industry without considering the effect of carbon capture on process emissions.

Due to the assumption of a 71% decarbonised power industry in 2050 and electricity efficiency improvements, the indirect emissions from the lime industry in 2050 are very low.

In conclusion, their prediction of the emission reduction potential is -31% by 2050 compared to 2010 levels which results in 18 Mt CO_2 in 2050 compared to 26 Mt CO_2 in 2010.

3.5.8.2 Technology Overview

The study analyses the abatement potentials under three subtitles: energy efficiency, lower carbon energy sources and end-of-pipe solutions. The measures are presented in the technology table in the annex.

They also mentioned some further measures to decrease emissions such as effective insulation, optimal combustion process, improved process and input control, optimal change-over management.

3.5.8.3 Industry contribution in emission reduction in other industries

In the study, there are several applications of lime given as emission reduction enabler.

- Hemp lime concrete is an insulating, breathable building material. Using lime as a binding material allows inclusion of organic material hemp in concrete which finally leads to a reduction of emissions of concrete.
- Innovations in lime production lead to 90% lower dust emission which leads to reduced environmental impacts
- Lime products are used to remove hydrocarbons from metallurgical residues and metal containing sludge, improving the recovery potential of these metals

- Within a project called Ecoloop, Lime was used as the transport medium, pollutant-bonding material, and catalyst. The aim of the project is to produce syngas without any flue gas.
- Carbonation of Lime: the reverse action in which lime is produced from limestone. After hydration of lime products it can capture atmospheric CO_2 and form $CaCO_3$. For mortar, in 100 years, 80-92% carbonation can take place which means around 2% of emissions resulting from lime production can be reversed by carbonation.

3.6 Non Ferrous Metal Industry

3.6.1 EAA 2012 Aluminium low-carbon roadmap

EAA 2012 An aluminium 2050 roadmap to a low-carbon Europe, 6 pages

Table 42: EAA 2012, general information

Carried out and Commissioned by:	European Aluminium Association
Link:	https://european-aluminium.eu/media/1801/201202-an-aluminium-2050-roadmap-to-a-low-carbon-europe.pdf
Range of emission reductions achieved	-31% (2050 vs. 1990)
Aim:	The paper is the response of the aluminium industry to the challenges in the low carbon roadmap published by the European Commission in 2011. It underlines that the industry will invest in Europe if conditions are favourable and that it will not survive in the EU if electricity cannot be purchased at internationally competitive prices. The paper urges for political measures to limit energy cost and support innovation.
Sectoral coverage:	Aluminium
Geography:	EU
Time horizon:	1990-2050
Modelling approach:	The study builds on the reductions projected by the European Commission for the electricity sector. No details on the methodology to arrive at the stated reduction potential are given.
General Assumptions:	It is assumed that the EU electricity sector will achieve the CO_2 intensity reductions projected by the European Commission (-92%) and that the aluminium sector will be able to purchase that electricity at internationally competitive prices.
Other aspects	The reduction potential of direct emissions of the aluminium industry is estimated at -70% in absolute terms which together with a reduction in indirect emissions from electricity results in -79% reduction potential from 1990-2050. With around 32 Mt direct emissions in 1990 a -70% reduction corresponds to a reduction of 22 Mt to a level of 10 Mt in 2050. The study points to international trade and carbon leakage since the carbon footprint of imported metal would be higher.

3.6.1.1 Scenario descriptions and main assumptions

The reduction potential of the aluminium industry is given below. The study does not provide detailed explanations about how these reductions are achieved.

Direct emissions (resulting from metal production, PFC emissions, semi-production, recycling) can be reduced by -70% in absolute terms compared to 1990 which results in 22 Mt CO_2. reduction.

Indirect emissions can have a further -9% reduction due to the decarbonization of the power industry which leads to 1 Mt CO_2. more reduction.

3.6.1.2 Technology Overview

In the study, it is mentioned that by conventional means, the industry reduced its emissions as far as possible and further reductions in direct emissions are depending upon breakthrough technologies. A reduction in power consumption is also limited with current technologies, thus according to the study, affordable clean energy is essential for further indirect emission reductions without carbon leakage.

Table 43: EAA 2012 Aluminium industry technology overview

Technology	Short Description	CO_2 Saving Potential*	Status	Advantages (+) / Restrictions (-)	Cost of the Technology
New technologies to replace carbon anode consumption	Substitution of carbon anode consumption which is currently the only technology for smelting/electrolysis	n.a	R&D, expected to be commercialized in 2030	n.a	n.a
Recycling	Using scrap aluminium instead of primary production	95% energy saving compared to primary production	n.a	Leakage of Aluminium scrap to the other countries (-)	n.a

3.6.1.3 Industry contribution in emission reduction in other industries

According to the study, through the use of Aluminium in transport, due to its lightweight, 70 Million tons CO_2 are being saved per annum. Further reductions can be achieved from the usage of aluminium in packaging, or energy efficient buildings.

The study also mentions the importance of keeping the aluminium production in Europe. The demand in Europe is steadily increasing unlike the production. Due to the high energy prices in Europe, especially primary aluminium production is decreasing in the EU. The study claims that without primary and recycled aluminium production in the EU the emissions would increase 178%.

4 Appendix 2: Methodological aspects and technologies

4.1 Calculation of direct emissions for the studies

The sector roadmaps have different scopes of analysis. To enable a meaningful comparison, all reduction potentials have been adjusted to cover only direct sector emissions. The following lists the original figures from the studies (see Table 44) and describes the different recalculation steps.

- **COM 2011 Low-carbon economy (LCE) roadmap and related impact assessment**: The study provides only percentage reductions derived from modelling based on PRIMES data. We calculated industry emissions as: energy-related CO_2 emission data for industry in PRIMES (781.4 Mt CO_2) + non-energy-related CO_2 emissions from PRIMES (329 Mt CO_2), both taken from the COM document "EU energy trends to 2030 — UPDATE 2009" (COM 2011c). This results in 1,111 Mt CO_2 emissions. These emission levels for 1990 were then multiplied by the relative reductions stated in the LCE roadmap to derive absolute emission levels for 2050.
- **COM 2011 Low-carbon economy (LCE) roadmap and related impact assessment - focus on energy-intensive industries:** The study provides only percentage reductions derived from modelling based on PRIMES data. We calculated energy-intensive industry emissions as follows: energy-related CO_2 emission data for energy-intensive industries in PRIMES (550.7 Mt CO_2) + non-energy-related CO_2 emissions from PRIMES (329 Mt CO_2). Both data sets were taken from the COM document EU energy trends to 2030 — UPDATE 2009 (COM 2011c). This results in 880 Mt CO_2 emissions. These emission levels for 1990 were multiplied by the relative reductions to derive the absolute emission levels for 2050.
- **Fraunhofer ISI 2012 Energy Efficiency for Climate Protection**: The study relies on PRIMES data but does not provide either total or direct emission levels for 1990. The study calculates emission levels based on primary energy demand from the PRIMES baseline. For the purpose of the comparison here, 1990 direct emissions are established as energy-related CO_2 emissions in the industrial sector from PRIMES: 781.4 Mt CO_2 are taken from the COM document: EU energy trends to 2030 — UPDATE 2009 (COM 2011c).
- **Fraunhofer ISI 2014 Energy efficiency/saving potentials until 2020 and beyond**; data taken directly from the study
- **BMUB 2015**: data taken directly from study where available; if necessary, additional information on 1990 levels was taken from the German Inventory, drawn from the UNFCCC webpage, August 2017
- **BCG 2013 Steel's contribution to low-carbon Europe**:For 1990:
  1) Specific emissions and production volumes by processes for 1990 taken from the paper.
  2) Based on the paper, 50% of EAF emissions deducted as indirect emissions. For BOF or OHF, indirect emissions are limited; therefore, for both processes, a lump sum deduction of 5% was made for indirect emissions.
  3) Specific emissions are multiplied by production amount and direct emission share.
  Similar to 1990 for 2050, it is assumed that half the EAF emissions are indirect emissions. In combination with the electricity emission factor, a specific electricity consumption per ton of crude steel based on EAF is calculated as 568 kWh. For the minimum reduction scenario, electricity efficiency improvements are not mentioned and hence assumed to be absent. The total share of production from EAF will be 44% according to the paper (104Mt CS). The target specific emissions from EAF in 2050 are given as 341 kgCO_2/tCS as well as the estimated emission factor of electricity production in 2050 (210 g CO_2/kWh). From all the information, the direct emissions from EAF can be calculated. For BF BOF, assumptions from 1990 can be used. In the max. abatement scenario on p. 17, it is mentioned that increase of renewables in the energy mix enable a further 15% reduction

in specific emissions, which results in 21 Mt CO_2 in total. This amount is also an emission reduction from purchased electricity.

- **JRC 2012**: A scaling factor based on NIR 2016 data for 2009 emissions was applied to establish 1990 emissions based on NIR but corresponding roughly to the study's scope. Total CO_2 emissions from combustion and process emissions minus recovery are 142.6 Mt CO_2 and 2009 emissions from the study are 185 Mt CO_2.
- **EUROFER 2013 Steel low-carbon roadmap** see BCG 2013
- **van Ruijven et al. 2016 steel** Total emissions for 2010 taken directly from the text. Direct emissions are taken from a graph since no figures are given in the study.
- **UBA 2014 THGND:** data taken directly from study where available; if necessary, additional information on 1990 levels were taken from the German Inventory, drawn from the UNFCCC webpage, August 2017
- **CEMBUREAU 2013 Cement low-carbon roadmap**: 1990 total emission levels are provided in the study itself. Absolute reduction potential is taken from the studies, percentages are calculated by ISI. Numerical values for direct emissions in 1990 and 2050 are taken directly from the study.
- **IEA 2009** The base year is 2006. The global cement industry's emission level in 1990 is not available. Direct emissions are given neither for the base year nor for 2050 and could not be calculated due to lack of information.
- van Ruijven et al. 2016 cement GHG emissions in 2010 direct+indirect emissions taken directly from the text. Emissions in the mitigation scenarios and direct emissions taken from a graph.
- **Ceramie-Unie 2013** Total emissions for 1990 are provided in the study itself. Direct emission values are derived from graphs given in the studies. Absolute reduction potential is taken from the studies, percentages are calculated by ISI.
- **Ecofys 2014 Lime low-carbon roadmap** The base year of the study is 2010. No 1990 figures are given. The study indicates that indirect emissions account for only 2% of total emissions. Calculations are done according to that information. Process emissions for the lime sector in 1990 in the inventory are 25,706 Mt CO_2, but total direct emissions cannot be established because there is no separate information on energy-related emissions for lime but only for the non-metallic minerals sector in total.
- **CEPI 2011 Pulp and paper low-carbon roadmap** 1990 total emission levels are provided in the study itself by categories and can be separated into direct vs. indirect emissions. Absolute reduction potential in Mt CO_2eq. is taken from the studies, percentages are calculated by ISI. Numerical values for direct emissions in 1990 and 2050 are taken directly from the studies.
- **EAA 2012 Aluminium low-carbon roadmap** Total emissions for 1990 are provided in the study itself. Direct emission values are derived from graphs given in the studies. Absolute reduction potential is taken from the studies, percentages are calculated by ISI.
- **CEFIC 2013 Chemistry future** The paper states emissions of 235 Mt CO_2eq. in 2010 and mentions that 2010 emissions are already being halved compared to 1990 levels. This gives 470 Mt CO_2eq. emissions in 1990. Direct emission levels for 1990 are established as 324 Mt CO_2eq. based on the "Annual European Union greenhouse gas inventory 1990–2014 and inventory report 2016". The direct emission levels for 2050 for all scenarios except "Continued Fragmentation" are equal to the total emission figures, since the paper assumes 100% decarbonisation of the electricity sector. For the scenario "Continued Fragmentation", the level of direct emissions is taken from the graph in the results section.

Table 44: Total and direct emissions for the selected studies

Study reference	1990 emission (Mt)	2050 emission (Mt) (low reduction)	2050 emission (Mt) (high reduction)	Percentage reduction 1990-2050 min. (%)	Percentage reduction 1990-2050 max. (%)	Correction value for indirect emissions	1990 direct emissions (Mt)	2050 direct emissions (Mt) (low reduction)	2050 direct emissions (Mt) (high reduction)	Percentage reduction 1990-2050 max. (%)
COM 2011 Low-carbon roadmap and impact assessment – total industry	*1111*	*189*	*144*	-83%	-87%	n.a.	*1111*	*189*	*144*	-87%
COM 2011 Low-carbon roadmap and impact assessment –EII results	*880*	*590*	*106*	-33%	-88%	n.a.	*880*	*589*	*106*	-88%
ISI 2012 Energy Efficiency for Climate Protection	*n.a. (1072 for 2010)*	n.a.	233	n.a.	*n.a.*	n.a.	*781*	*n.a.*	*233*	*-70%*
ISI 2014 Energy efficiency/ saving potentials until 2020 and beyond	*781*	n.a.	n.a. (355 for 2030)	n.a.	n.a. (-55% for 2030)	0	*781*	n.a.	n.a. (355 for 2030)	n.a. (-55% for 2030)
BMUB 2015 WMS	n.a. (108 for energy)	n.a.	92.5	n.a.	n.a.	n.a.	n.a.	92.5	n.a.	n.a.
BMUB 2015 CS 80	n.a. (108 for energy)	n.a.	54.6	n.a.	n.a.	n.a.	n.a.	54.6	n.a.	n.a.
BMUB 2015 CS 95	n.a. (108 for energy)	n.a.	-3.8	n.a.	n.a.	n.a.	n.a.	-3.8	n.a.	n.a.

Study reference	1990 emission (Mt)	2050 emission (Mt) (low reduction)	2050 emission (Mt) (high reduction)	Percentage reduction 1990-2050 min. (%)	Percentage reduction 1990-2050 max. (%)	Correction value for indirect emissions	1990 direct emissions (Mt)	2050 direct emissions (Mt) (low reduction)	2050 direct emissions (Mt) (high reduction)	Percentage reduction 1990-2050 max. (%)
BCG 2013 Steel's contribution to low-carbon Europe	298	270	130	*-9%*	*-56%*	-32	*266*	*246*	*113*	*-58%*
JRC 2012	n.a. (185 for 2009)	n.a. (161 for 2030)	n.a. (149 for 2030)	n.a. (-13% for 2009-2030)	n.a. (-20% for 2009-2030)	166	352	n.a. (161 for 2030)	n.a. (149 for 2030)	n.a. (-20% for 2009-2030)
EUROFER 2013 Steel low-carbon roadmap	298	168	40	*-44%*	*-87%*	n.a.	n.a.	n.a.	n.a.	*n.a.*
Van Ruijven et al. 2016 steel	n.a. (3250 for 2010)	*900*	*300*	n.a. (-70% for 2010-2050)	n.a. (-90% for 2010-2050)	-950	n.a. (2300 for 2010)	800	200	n.a. (-90% for 2010-2050)
UBA 2014 THGND	n.a.	n.a.	13.8	n.a.	n.a.	n.a.	n.a.	n.a.	13.8	n.a.
CEMBUREAU 2013 Cement low-carbon roadmap	170	136	54	*-20%*	*-68%*	-13	157	112	33	*-79%*
IEA 2009	n.a. (2047 for 2006)	2521	1548	n.a. (+23% for 2006-2050)	n.a. (-24% for 2006-2050)	n.a.	n.a.	n.a.	n.a.	n.a. (-24% for 2006-2050)
Van Ruijven et al. 2016 cement	n.a. (3050 for 2010)	*2050*	*500*	n.a. (-33% for 2010-2050)	n.a. (-76% for 2010-2050)	-550	n.a. (2500 for 2010)	2000	500	n.a. (-80% for 2010-2050)
Ceramie-Unie 2013	22	9	5	*-59%*	*-77%*	0	22	9	5	*-77%*

Study reference	**1990 emission (Mt)**	**2050 emission (Mt) (low reduction)**	**2050 emission (Mt) (high reduction)**	**Percentage reduction 1990-2050 min. (%)**	**Percentage reduction 1990-2050 max. (%)**	**Correction value for indirect emissions**	**1990 direct emissions (Mt)**	**2050 direct emissions (Mt) (low reduction)**	**2050 direct emissions (Mt) (high reduction)**	**Percentage reduction 1990-2050 max. (%)**
Ecofys Lime low-carbon roadmap	n.a. (26 for 2010)	n.a.	18	n.a.	n.a. (-31% for 2010-2050)	-1	25 (2010)	n.a.	18	n.a. (-31% for 2010-2050)
CEPI 2011 Pulp and paper low-carbon roadmap	60	48	34	*-20%*	*-43%*	-20	40	56	10	*-75%*
EAA 2012 Aluminium low-carbon roadmap	52	n.a.	41	n.a.	*-21%*	-20	32	n.a.	22	*-31%*
CEFIC 2013 Chemistry future	*470*	445	350	*-5%*	*-26%*	-146	*324*	*200*	*94*	*-71%*

4.2 Scenario table

Table 45: NIR category coverage of the different studies

Scenarios		*Scope*					*Results*				*Key assumptions*				
Reference	***Scenario-ID***	***GHG coverage***	***GEO***	***Base year***	***Coverage of relevant NIR emissions***	***GHG emissions in 1990 (Mt CO_2eq.)***	***GHG emissions in 2030 (Mt CO_2)***	***GHG emissions in 2050 (Mt CO_2)***	***GHG reduction in 2030 vs. 1990***	***GHG reduction in 2050 vs. 1990***	***Rationale behind GHG reduction***	***Technology***	***Production in 2050 vs. 2010***	***Carbon price in 2050***	***Energy prices***
Entire industry sector															
UBA (2014)	THGND	All GHGs included	DE	1990	100%	n.a.	n.a.	14	n.a.	n.a.	Technical limits	Breakthrough without CCS	Physical production provided in detail for several different products in the study	n.a	n.a

Scenarios		***Scope***					***Results***				***Key assumptions***				
Reference	***Scenario-ID***	***GHG coverage***	***GEO***	***Base year***	***Coverage of relevant NIR emissions***	***GHG emissions in 1990 (Mt CO_2eq.)***	***GHG emissions in 2030 (Mt CO_2)***	***GHG emissions in 2050 (Mt CO_2)***	***GHG reduction in 2030 vs. 1990***	***GHG reduction in 2050 vs. 1990***	***Rationale behind GHG reduction***	***Technology***	***Production in 2050 vs. 2010***	***Carbon price in 2050***	***Energy prices***
BMUB (2015)	EMS (2012)	All GHGs included	DE	1990	100%	272	155	130	43%	52%	Policies and measures	Standard	Physical production provided in detail for several different products in the study	50	Oil: high Gas: medium Coal: low
BMUB (2015)	CS 80	All GHGs included	DE	1990	100%	272	121	70	56%	74%	Policies and measures	Standard	Physical production provided in detail for several different products in the study	130	Oil: high Gas: medium Coal: low

Scenarios		***Scope***					***Results***				***Key assumptions***				
Reference	***Scenario-ID***	***GHG coverage***	***GEO***	***Base year***	***Coverage of relevant NIR emissions***	***GHG emissions in 1990 (Mt CO_2eq.)***	***GHG emissions in 2030 (Mt CO_2)***	***GHG emissions in 2050 (Mt CO_2)***	***GHG reduction in 2030 vs. 1990***	***GHG reduction in 2050 vs. 1990***	***Rationale behind GHG reduction***	***Technology***	***Production in 2050 vs. 2010***	***Carbon price in 2050***	***Energy prices***
BMUB (2015)	CS 95	All GHGs included	DE	1990	100%	272	97	1	64%	100%	Technical limits	Standard with CCS	Physical production provided in detail for several different products in the study	200	Oil: high Gas: medium Coal: low
COM (2011)	Reference - frag. action, oil shock	CO_2 only	EU27	1990	83%	1111	700	744	37%	33%	Economics	Standard	n.a	€ 50	Coal: Oil: Electricity: Gas:

Scenarios		***Scope***					***Results***				***Key assumptions***				
Reference	***Scenario-ID***	***GHG coverage***	***GEO***	***Base year***	***Coverage of relevant NIR emissions***	***GHG emissions in 1990 (Mt CO_2eq.)***	***GHG emissions in 2030 (Mt CO_2)***	***GHG emissions in 2050 (Mt CO_2)***	***GHG reduction in 2030 vs. 1990***	***GHG reduction in 2050 vs. 1990***	***Rationale behind GHG reduction***	***Technology***	***Production in 2050 vs. 2010***	***Carbon price in 2050***	***Energy prices***
COM (2011)	Reference - frag. action, ref fossil fuel prices	CO_2 only	EU27	1990	83%	1111	744	733	33%	34%	Economics	Standard	n.a	€ 50	Coal: - Oil: medium Electricity: n.a Gas: n.a
COM (2011)	Reference - frag. action, high fossil fuel prices	CO_2 only	EU27	1990	83%	1111	700	711	37%	36%	Economics	Standard	n.a	€ 50	Coal: low Oil: high Electricity: n.a Gas: medium

Scenarios		***Scope***					***Results***				***Key assumptions***				
Reference	***Scenario-ID***	***GHG coverage***	***GEO***	***Base year***	***Coverage of relevant NIR emissions***	***GHG emissions in 1990 (Mt CO_2eq.)***	***GHG emissions in 2030 (Mt CO_2)***	***GHG emissions in 2050 (Mt CO_2)***	***GHG reduction in 2030 vs. 1990***	***GHG reduction in 2050 vs. 1990***	***Rationale behind GHG reduction***	***Technology***	***Production in 2050 vs. 2010***	***Carbon price in 2050***	***Energy prices***
COM (2011)	Effect. techn. + lower EII effort - frag. action, ref. fossil fuel prices	CO_2 only	EU27	1990	83%	1111	744	511	33%	54%	Economics	Standard with CCS	n.a	€ 147	Coal: - Oil: medium Electricity: n.a Gas: n.a
COM (2011)	Effect. techn. - frag. action, oil shock	CO_2 only	EU27	1990	83%	1111	667	189	40%	83%	Economics	Standard with CCS	n.a	€ 117	Coal: n.a. Oil: n.a. Electricity: n.a. Gas: n.a.

Scenarios		***Scope***					***Results***				***Key assumptions***				
Reference	***Scenario-ID***	***GHG coverage***	***GEO***	***Base year***	***Coverage of relevant NIR emissions***	***GHG emissions in 1990 (Mt CO_2eq.)***	***GHG emissions in 2030 (Mt CO_2)***	***GHG emissions in 2050 (Mt CO_2)***	***GHG reduction in 2030 vs. 1990***	***GHG reduction in 2050 vs. 1990***	***Rationale behind GHG reduction***	***Technology***	***Production in 2050 vs. 2010***	***Carbon price in 2050***	***Energy prices***
COM (2011)	Effect. techn. - global action, low fossil fuel prices	CO_2 only	EU27	1990	83%	1111	722	178	35%	84%	Economics	Standard with CCS	n.a	€ 190	Coal: low Oil: medium Electricity: n.a Gas: high
COM (2011)	Effect. techn. – frag. action, ref. fossil fuel prices	CO_2 only	EU27	1990	83%	1111	711	178	36%	84%	Economics	Standard with CCS	n.a	€ 147	Coal: n.a. Oil: medium Electricity: n.a Gas: n.a.

Scenarios		*Scope*					*Results*				*Key assumptions*				
Reference	***Scenario-ID***	***GHG coverage***	***GEO***	***Base year***	***Coverage of relevant NIR emissions***	***GHG emissions in 1990 (Mt CO_2eq.)***	***GHG emissions in 2030 (Mt CO_2)***	***GHG emissions in 2050 (Mt CO_2)***	***GHG reduction in 2030 vs. 1990***	***GHG reduction in 2050 vs. 1990***	***Rationale behind GHG reduction***	***Technology***	***Production in 2050 vs. 2010***	***Carbon price in 2050***	***Energy prices***
COM (2011)	Effect. techn. - frag. action, high fossil f. prices	CO_2 only	EU27	1990	83%	1111	678	178	39%	84%	Economics	Standard with CCS	n.a	€ 104	Coal: n.a. Oil: medium Electricity: n.a. Gas: n.a.
COM (2011)	Effect. techn. + delay. Electrification - global action, low fossil fuel prices	CO_2 only	EU27	1990	83%	1111	722	167	35%	85%	Economics	Standard with CCS	n.a	€ 245	Coal: low Oil: medium Electricity: n.a Gas: high

Scenarios		***Scope***					***Results***				***Key assumptions***				
Reference	***Scenario-ID***	***GHG coverage***	***GEO***	***Base year***	***Coverage of relevant NIR emissions***	***GHG emissions in 1990 (Mt CO_2eq.)***	***GHG emissions in 2030 (Mt CO_2)***	***GHG emissions in 2050 (Mt CO_2)***	***GHG reduction in 2030 vs. 1990***	***GHG reduction in 2050 vs. 1990***	***Rationale behind GHG reduction***	***Technology***	***Production in 2050 vs. 2010***	***Carbon price in 2050***	***Energy prices***
COM (2011)	Delay clim. act. - frag. action, ref. fossil fuel prices	CO_2 only	EU27	1990	83%	1111	744	144	33%	87%	Economics	Standard with CCS	n.a	€ 250	Coal: n.a. Oil: medium Electricity: n.a. Gas: n.a.
COM (2011)	Effect. techn. + delay CCS - global action, low fossil fuel prices	CO_2 only	EU27	1990	83%	1111	733	144	34%	87%	Economics	Standard with CCS	n.a	€ 370	Coal: low Oil: medium Electricity: n.a Gas: high

Scenarios		***Scope***					***Results***				***Key assumptions***				
Reference	***Scenario-ID***	***GHG coverage***	***GEO***	***Base year***	***Coverage of relevant NIR emissions***	***GHG emissions in 1990 (Mt CO_2eq.)***	***GHG emissions in 2030 (Mt CO_2)***	***GHG emissions in 2050 (Mt CO_2)***	***GHG reduction in 2030 vs. 1990***	***GHG reduction in 2050 vs. 1990***	***Rationale behind GHG reduction***	***Technology***	***Production in 2050 vs. 2010***	***Carbon price in 2050***	***Energy prices***
COM (2011)	Delay. Clim. act. - glob. action, low fossil fuel prices	CO_2 only	EU27	1990	83%	1111	767	133	31%	88%	Economics	Standard with CCS	n.a	€ 190	Coal: low Oil: medium Electricity: n.a Gas: high
COM (2011)	EII: Reference scenario - frag. action, ref. fossil fuel prices	CO_2 only	EU27	1990	92%	880	616	590	30%	33%	Economics	Standard with CCS	n.a	€ 50	Coal: low Oil: high Electricity: n.a Gas: medium

Scenarios		***Scope***					***Results***				***Key assumptions***				
Reference	***Scenario-ID***	***GHG coverage***	***GEO***	***Base year***	***Coverage of relevant NIR emissions***	***GHG emissions in 1990 (Mt CO_2eq.)***	***GHG emissions in 2030 (Mt CO_2)***	***GHG emissions in 2050 (Mt CO_2)***	***GHG reduction in 2030 vs. 1990***	***GHG reduction in 2050 vs. 1990***	***Rationale behind GHG reduction***	***Technology***	***Production in 2050 vs. 2010***	***Carbon price in 2050***	***Energy prices***
COM (2011)	EII: Effect. techn. + lower EII effort - frag. action, ref. fossil fuel prices	CO_2 only	EU27	1990	92%	880	607	431	31%	51%	Economics	Standard - with CCS	n.a	€ 147	Coal: - Oil: medium Electricity: n.a Gas: n.a
COM (2011)	EII: Effect. techn. - frag. action, ref. fossil fuel prices	CO_2 only	EU27	1990	92%	880	581	114	34%	87%	Economics	Standard with CCS	n.a	€ 147	Coal: - Oil: medium Electricity: n.a Gas: n.a

Scenarios		***Scope***					***Results***				***Key assumptions***				
Reference	***Scenario-ID***	***GHG coverage***	***GEO***	***Base year***	***Coverage of relevant NIR emissions***	***GHG emissions in 1990 (Mt CO_2eq.)***	***GHG emissions in 2030 (Mt CO_2)***	***GHG emissions in 2050 (Mt CO_2)***	***GHG reduction in 2030 vs. 1990***	***GHG reduction in 2050 vs. 1990***	***Rationale behind GHG reduction***	***Technology***	***Production in 2050 vs. 2010***	***Carbon price in 2050***	***Energy prices***
COM (2011)	EII: Effect. techn. - global action, low fossil fuel prices	CO_2 only	EU27	1990	92%	880	581	106	34%	88%	Economics	Standard with CCS	n.a	€ 190	Coal: low Oil: medium Electricity: n.a Gas: high
ISI (2012)	No scenario	CO_2 only	EU27	2010 (adjusted to 1990 based on PRIMES)	58%	781	616	233	21%	70%	Economics	Standard	n.a	n.a	Coal: low Oil: medium Electricity: n.a Gas: medium

Scenarios		***Scope***					***Results***				***Key assumptions***				
Reference	***Scenario-ID***	***GHG coverage***	***GEO***	***Base year***	***Coverage of relevant NIR emissions***	***GHG emissions in 1990 (Mt $CO_2eq.$)***	***GHG emissions in 2030 (Mt CO_2)***	***GHG emissions in 2050 (Mt CO_2)***	***GHG reduction in 2030 vs. 1990***	***GHG reduction in 2050 vs. 1990***	***Rationale behind GHG reduction***	***Technology***	***Production in 2050 vs. 2010***	***Carbon price in 2050***	***Energy prices***
ISI (2014)	Potential 2030 HPI, 40% GHG reduction target	CO_2 only	EU27	1990 (from PRIMES)	58%	781	447	n.a	43%	n.a	Economics	Standard	n.a	n.a (€ 50 in 2030)	Coal: low Oil: medium Electricity: n.a Gas: medium
ISI (2014)	Potential 2030 HPI 100% economic potential, 27% RES, 41% thermal eff.	CO_2 only	EU27	1990 (from PRIMES)	58%	781	401	n.a	49%	n.a	Economics	Standard	n.a	n.a (€ 50 in 2030)	Coal: low Oil: medium Electricity: n.a Gas: medium

Scenarios		*Scope*					*Results*				*Key assumptions*				
Reference	***Scenario-ID***	***GHG coverage***	***GEO***	***Base year***	***Coverage of relevant NIR emissions***	***GHG emissions in 1990 (Mt CO_2eq.)***	***GHG emissions in 2030 (Mt CO_2)***	***GHG emissions in 2050 (Mt CO_2)***	***GHG reduction in 2030 vs. 1990***	***GHG reduction in 2050 vs. 1990***	***Rationale behind GHG reduction***	***Technology***	***Production in 2050 vs. 2010***	***Carbon price in 2050***	***Energy prices***
ISI (2014)	Potential 2030 HPI 100% economic potential, 35% RES, 43% thermal eff.	CO_2 only	EU27	1990 (from PRIMES)	58%	781	355	n.a	55%	n.a	Economics	Standard	n.a	n.a (€ 50 in 2030)	Coal: low Oil: medium Electricity: n.a Gas: medium
Iron and steel															
UBA (2014)	THGND	All GHGs included	DE	2010	100%	n.a.	n.a.	0	n.a.	99.7% to 2010	Technical limits	Breakthrough without CCS	3% (45 Mt)	n.a.	n.a.
BMUB (2015)	EMS (2012)	All GHGs included	DE	1990	100% (39%)	58 (23)	14	10	40%	54%	Policies and measures	Standard	-8%	50	Oil: high Gas: medium Coall: low

Scenarios		***Scope***					***Results***				***Key assumptions***				
Reference	***Scenario-ID***	***GHG coverage***	***GEO***	***Base year***	***Coverage of relevant NIR emissions***	***GHG emissions in 1990 (Mt CO_2eq.)***	***GHG emissions in 2030 (Mt CO_2)***	***GHG emissions in 2050 (Mt CO_2)***	***GHG reduction in 2030 vs. 1990***	***GHG reduction in 2050 vs. 1990***	***Rationale behind GHG reduction***	***Technology***	***Production in 2050 vs. 2010***	***Carbon price in 2050***	***Energy prices***
BMUB (2015)	CS 80	All GHGs included	DE	1990	100% (39%)	58 (23)	12	7	47%	69%	Policies and measures	Standard	-8%	130	Oil: high Gas: medium Coall: low
BMUB (2015)	CS 95	All GHGs included	DE	1990	100% (39%)	58 (23)	11	0	52%	98%	Technical limits	Standard with CCS	-13%	200	Oil: high Gas: medium Coall: low
Van Ruijven et al. (2016)	Baseline	CO_2 only	Global	2010	n.a	n.a	n.a	1600	n.a	n.a	Economics	Standard	n.a	€ -	n.a
van Ruijven et al. (2016)	20$ / tCO2	CO_2 only	Global	2010	n.a	n.a	n.a	750	n.a	n.a	Economics	Standard without CCS	n.a	€ 65	n.a

Scenarios		***Scope***					***Results***				***Key assumptions***				
Reference	***Scenario-ID***	***GHG coverage***	***GEO***	***Base year***	***Coverage of relevant NIR emissions***	***GHG emissions in 1990 (Mt CO_2eq.)***	***GHG emissions in 2030 (Mt CO_2)***	***GHG emissions in 2050 (Mt CO_2)***	***GHG reduction in 2030 vs. 1990***	***GHG reduction in 2050 vs. 1990***	***Rationale behind GHG reduction***	***Technology***	***Production in 2050 vs. 2010***	***Carbon price in 2050***	***Energy prices***
Van Ruijven et al. (2016)	20$ / tCO2 - with CCS	CO_2 only	Global	2010	n.a	n.a	n.a	500	n.a	n.a	Economics	Standard with CCS	n.a	€ 65	n.a
Van Ruijven et al. (2016)	50$ / tCO2	CO_2 only	Global	2010	n.a	n.a	n.a	500	n.a	n.a	Economics	Standard without CCS	n.a	€ 162	n.a
van Ruijven et al. (2016)	100$ / tCO2	CO_2 only	Global	2010	n.a	n.a	n.a	500	n.a	n.a	Economics	Standard without CCS	n.a	€ 324	n.a
Van Ruijven et al. (2016)	50$ / tCO2 - with CCS	CO_2 only	Global	2010	n.a	n.a	n.a	300	n.a	n.a	Economics	Standard with CCS	n.a	€ 162	n.a
Van Ruijven et al. (2016)	100$ / tCO2 - with CCS	CO_2 only	Global	2010	n.a	n.a	n.a	200	n.a	n.a	Economics	Standard with CCS	n.a	€ 324	n.a
Wyns and Axelson (2016)	No scenario	CO_2, CH_4, N_2O	EU28	1990	100%	272	n.a	54	n.a	80%	Technical limits	Breakthrough without CCS	n.a	n.a	n.a

Scenarios		***Scope***					***Results***				***Key assumptions***				
Reference	***Scenario-ID***	***GHG coverage***	***GEO***	***Base year***	***Coverage of relevant NIR emissions***	***GHG emissions in 1990 (Mt CO_2eq.)***	***GHG emissions in 2030 (Mt CO_2)***	***GHG emissions in 2050 (Mt CO_2)***	***GHG reduction in 2030 vs. 1990***	***GHG reduction in 2050 vs. 1990***	***Rationale behind GHG reduction***	***Technology***	***Production in 2050 vs. 2010***	***Carbon price in 2050***	***Energy prices***
DECC (2015)*	BAU	CO_2 only	UK	2013	n.a.	n.a.	n.a.	20	n.a.	n.a.	Economics	Standard	n.a.	n.a.	n.a.
DECC (2015)*	Max. technology	CO_2 only	UK	2013	n.a.	n.a.	n.a.	9	n.a.	n.a.	Technical limits	Breakthrough with CCS	n.a.	n.a.	n.a.
JRC (2012)	Alternative Scenario 1 (2x Fuel)	CO_2 only	EU27	2009	129%	352	161	n.a	54%	n.a	Economics	Standard with CCS	43% by 2030	€ 39	Coal: medium Oil: n.a Electricity: medium Gas: medium

Scenarios		***Scope***					***Results***				***Key assumptions***				
Reference	***Scenario-ID***	***GHG coverage***	***GEO***	***Base year***	***Coverage of relevant NIR emissions***	***GHG emissions in 1990 (Mt CO_2eq.)***	***GHG emissions in 2030 (Mt CO_2)***	***GHG emissions in 2050 (Mt CO_2)***	***GHG reduction in 2030 vs. 1990***	***GHG reduction in 2050 vs. 1990***	***Rationale behind GHG reduction***	***Technology***	***Production in 2050 vs. 2010***	***Carbon price in 2050***	***Energy prices***
JRC (2012)	Baseline Scenario	CO_2 only	EU27	2009	129%	352	160	n.a	55%	n.a	Economics	Standard with CCS	43% by 2030	€ 39	Coal: medium Oil: n.a Electricity: medium Gas: medium
JRC (2012)	Alternative Scenario 2 (100€ /t CO_2)	CO2 only	EU27	2009	129%	352	158	n.a	55%	n.a	Economics	Breakthrough with CCS	43% by 2030	€ 100	Coal: medium Oil: n.a Electricity: medium Gas: medium

Scenarios		***Scope***					***Results***				***Key assumptions***				
Reference	***Scenario-ID***	***GHG coverage***	***GEO***	***Base year***	***Coverage of relevant NIR emissions***	***GHG emissions in 1990 (Mt CO_2eq.)***	***GHG emissions in 2030 (Mt CO_2)***	***GHG emissions in 2050 (Mt CO_2)***	***GHG reduction in 2030 vs. 1990***	***GHG reduction in 2050 vs. 1990***	***Rationale behind GHG reduction***	***Technology***	***Production in 2050 vs. 2010***	***Carbon price in 2050***	***Energy prices***
JRC (2012)	Alternative Scenario 1 (5x Fuel)	CO_2 only	EU27	2009	129%	352	157	n.a	55%	n.a	Economics	Standard with CCS	43% by 2030	€ 39	Coal: medium Oil: n.a Electricity: medium Gas: medium
JRC (2012)	Alternative Scenario 2 (200€-CO_2)	CO_2 only	EU27	2009	129%	352	149	n.a	58%	n.a	Economics	Breakthrough with CCS	43% by 2030	€ 200	Coal: medium Oil: n.a Electricity: medium Gas: medium

Scenarios		***Scope***					***Results***				***Key assumptions***				
Reference	***Scenario-ID***	***GHG coverage***	***GEO***	***Base year***	***Coverage of relevant NIR emissions***	***GHG emissions in 1990 (Mt CO_2eq.)***	***GHG emissions in 2030 (Mt CO_2)***	***GHG emissions in 2050 (Mt CO_2)***	***GHG reduction in 2030 vs. 1990***	***GHG reduction in 2050 vs. 1990***	***Rationale behind GHG reduction***	***Technology***	***Production in 2050 vs. 2010***	***Carbon price in 2050***	***Energy prices***
BCG (2013)	Economic Scenario – reference price	CO_2 only	EU27	1990	98%	266	n.a	n.a	n.a	n.a	Economics	Standard	37%	€ 259	n.a
BCG (2013)	Economic Scenario – medium price	CO_2 only	EU27	1990	98%	266	n.a	n.a	n.a	n.a	Economics	Standard	37%	€ 393	n.a
BCG (2013)	Economic Scenario – high price	CO_2 only	EU27	1990	98%	266	n.a	n.a	n.a	n.a	Economics	Standard	37%	€ 706	n.a
BCG (2013)	Baseline Upper Boundary	CO_2 only	EU27	1990	98%	266	n.a	270	n.a	-2%	Technical limits	Standard	37%	n.a	n.a
BCG (2013)	Continued improved efficiency Upper Boundary	CO_2 only	EU27	1990	98%	266	n.a	246	n.a	8%	Economics	Standard	37%	n.a	n.a

Scenarios		***Scope***					***Results***				***Key assumptions***				
Reference	***Scenario-ID***	***GHG coverage***	***GEO***	***Base year***	***Coverage of relevant NIR emissions***	***GHG emissions in 1990 (Mt CO_2eq.)***	***GHG emissions in 2030 (Mt CO_2)***	***GHG emissions in 2050 (Mt CO_2)***	***GHG reduction in 2030 vs. 1990***	***GHG reduction in 2050 vs. 1990***	***Rationale behind GHG reduction***	***Technology***	***Production in 2050 vs. 2010***	***Carbon price in 2050***	***Energy prices***
BCG (2013)	Lower theoretical boundary without CCUS	CO_2 only	EU27	1990	98%	266	n.a	165	n.a	38%	Technical limits	Breakthrough without CCS	37%	n.a	n.a
BCG (2013)	Lower theoretical boundary with CCUS	CO_2 only	EU27	1990	98%	266	n.a	113	n.a	58%	Technical limits	Breakthrough with CCS	37%	n.a	n.a
BCG (2013)	Drop in production	CO_2 only	EU27	1990	98%	266	n.a	n.a	n.a	n.a	Drop in production	Standard	37%	n.a	n.a
EUROFER (2013)	As in BCG (2013)	CO_2 only	EU27	1990	see BCG	see BCG	see BCG	see BCG	see BCG	see BCG	see BCG	see BCG	see BCG	see BCG	see BCG
Pulp and Paper															
UBA (2014)	THGND	All GHGs included	DE	2010	100%	12,19	n.a.	0	n.a.	100%	Technical limits	Breakthrough without CCS	0%	n.a.	n.a.

Scenarios		***Scope***					***Results***				***Key assumptions***				
Reference	***Scenario-ID***	***GHG coverage***	***GEO***	***Base year***	***Coverage of relevant NIR emissions***	***GHG emissions in 1990 (Mt CO_2eq.)***	***GHG emissions in 2030 (Mt CO_2)***	***GHG emissions in 2050 (Mt CO_2)***	***GHG reduction in 2030 vs. 1990***	***GHG reduction in 2050 vs. 1990***	***Rationale behind GHG reduction***	***Technology***	***Production in 2050 vs. 2010***	***Carbon price in 2050***	***Energy prices***
DECC (2015)	BAU	CO_2 only	UK	2012	n.a.	n.a.	n.a.	2	n.a.	n.a.	Economics	Standard	n.a.	n.a.	n.a.
DECC (2015)	Max. technology clustering and electrification	CO_2 only	UK	2012	n.a.	n.a.	n.a.	0	n.a.	n.a.	Technical limits	Breakthrough	n.a.	n.a.	n.a.
DECC (2015)	Max. technology biomass	CO_2 only	UK	2012	n.a.	n.a.	n.a.	0	n.a.	n.a.	Technical limits	Breakthrough with biomass	n.a.	n.a.	n.a.
CEPI (2011)	No scenario	CO_2 only	EU27	1990	115%	40	31	24	24%	40%	Technical limits	without CCS	n.a	n.a	n.a
CEPI (2011)	No scenario	CO_2 only	EU27	1990	115%	40	31	10	24%	75%	Technical limits	Breakthrough	n.a	€ 190	n.a
Chemicals															

Scenarios		***Scope***					***Results***				***Key assumptions***				
Reference	***Scenario-ID***	***GHG coverage***	***GEO***	***Base year***	***Coverage of relevant NIR emissions***	***GHG emissions in 1990 (Mt CO_2eq.)***	***GHG emissions in 2030 (Mt CO_2)***	***GHG emissions in 2050 (Mt CO_2)***	***GHG reduction in 2030 vs. 1990***	***GHG reduction in 2050 vs. 1990***	***Rationale behind GHG reduction***	***Technology***	***Production in 2050 vs. 2010***	***Carbon price in 2050***	***Energy prices***
UBA (2014)	THGND	All GHGs included	DE	2010	100%	n.a.	n.a.	0,5	n.a.	99%	Technical limits	Breakthrough without CCS	80%	n.a	n.a
BMUB (2015)	EMS (2012)	All GHGs included	DE	2010	100% (?)	30	15	13	51%	55%	Policies and measures	Standard	provided by product, aggregation not possible	50	Oil: high Gas: medium Coall: low
BMUB (2015)	CS 80	All GHGs included	DE	2010	100% (?)	30	14	11	54%	63%	Policies and measures	Standard	provided by product, aggregation not possible	130	Oil: high Gas: medium Coall: low

Scenarios		***Scope***					***Results***				***Key assumptions***				
Reference	***Scenario-ID***	***GHG coverage***	***GEO***	***Base year***	***Coverage of relevant NIR emissions***	***GHG emissions in 1990 (Mt CO_2eq.)***	***GHG emissions in 2030 (Mt CO_2)***	***GHG emissions in 2050 (Mt CO_2)***	***GHG reduction in 2030 vs. 1990***	***GHG reduction in 2050 vs. 1990***	***Rationale behind GHG reduction***	***Technology***	***Production in 2050 vs. 2010***	***Carbon price in 2050***	***Energy prices***
BMUB (2015)	CS 95	All GHGs included	DE	2010	100% (?)	30	11	1	63%	98%	Technical limits	Standard with CCS	provided by product, aggregation not possible	200	Oil: high Gas: medium Coall: low
DECC (2015)	BAU	CO_2 only	UK	2012	n.a.	n.a.	n.a.	13	n.a.	n.a.	Economics	Standard	n.a.	n.a.	n.a.
DECC (2015)	Max. technology	CO_2 only	UK	2012	n.a.	n.a.	n.a.	4	n.a.	n.a.	Technical limits	Breakthrough without CCS	n.a.	n.a.	n.a.
DECC (2015)	Max. technology with biomass	CO_2 only	UK	2012	n.a.	n.a.	n.a.	3,3	n.a.	n.a.	Technical limits	Breakthrough with CCS	n.a.	n.a.	n.a.
Wyns and Axelson (2016)	No scenario	All GHG included	EU28	1990	100%	325	n.a	585	n.a	80%	Technical limits	Breakthrough without CCS	n.a	n.a	n.a

Scenarios		***Scope***					***Results***				***Key assumptions***				
Reference	***Scenario-ID***	***GHG coverage***	***GEO***	***Base year***	***Coverage of relevant NIR emissions***	***GHG emissions in 1990 (Mt CO_2eq.)***	***GHG emissions in 2030 (Mt CO_2)***	***GHG emissions in 2050 (Mt CO_2)***	***GHG reduction in 2030 vs. 1990***	***GHG reduction in 2050 vs. 1990***	***Rationale behind GHG reduction***	***Technology***	***Production in 2050 vs. 2010***	***Carbon price in 2050***	***Energy prices***
CEFIC (2013)	Continued Fragmentation	CO_2, N_2O, PFCs, HFCs	EU27	1990	100%	324	n.a	223	n.a	31%	Economics	Standard	n.a	€ 53	Coal: medium Oil: high Electricity: medium Gas: medium
CEFIC (2013)	Level Playing Field	CO_2, N_2O, PFCs, HFCs	EU27	1990	100%	324	n.a	200	n.a	38%	Economics	Standard with CCS	n.a	€ 194	Coal: low Oil: medium Electricity: high Gas: medium

Scenarios		***Scope***					***Results***				***Key assumptions***				
Reference	***Scenario-ID***	***GHG coverage***	***GEO***	***Base year***	***Coverage of relevant NIR emissions***	***GHG emissions in 1990 (Mt CO_2eq.)***	***GHG emissions in 2030 (Mt CO_2)***	***GHG emissions in 2050 (Mt CO_2)***	***GHG reduction in 2030 vs. 1990***	***GHG reduction in 2050 vs. 1990***	***Rationale behind GHG reduction***	***Technology***	***Production in 2050 vs. 2010***	***Carbon price in 2050***	***Energy prices***
CEFIC (2013)	Isolated Europe	CO_2, N_2O, PFCs, HFCs	EU27	1990	100%	324	n.a	94	n.a	71%	Economics	Standard with CCS	n.a	€ 221	Coal: high Oil: high Electricity: high Gas: high
CEFIC (2013)	Differentiated Global Action	CO_2, N_2O, PFCs, HFCs	EU27	1990	100%	324	n.a	94	n.a	71%	Economics	Standard with CCS	n.a	€ 276	Coal: low Oil: medium Electricity: medium Gas: medium

Scenarios		***Scope***					***Results***				***Key assumptions***				
Reference	***Scenario-ID***	***GHG coverage***	***GEO***	***Base year***	***Coverage of relevant NIR emissions***	***GHG emissions in 1990 (Mt CO_2eq.)***	***GHG emissions in 2030 (Mt CO_2)***	***GHG emissions in 2050 (Mt CO_2)***	***GHG reduction in 2030 vs. 1990***	***GHG reduction in 2050 vs. 1990***	***Rationale behind GHG reduction***	***Technology***	***Production in 2050 vs. 2010***	***Carbon price in 2050***	***Energy prices***
Non-metallic minerals (Cement)															
BMUB (2015)	EMS (2012)	All GHGs included	DE	1990	100% (45%)	34 (15)	11	9	27%	41%	Policies and measures	Standard	-28%	50	Oil: high Gas: medium Coall: low
BMUB (2015)	CS 80	All GHGs included	DE	1990	100% (45%)	34 (15)	11	9	27%	41%	Policies and measures	Standard	-28%	130	Oil: high Gas: medium Coall: low
BMUB (2015)	CS 95	All GHGs included	DE	1990	100% (45%)	34 (15)	8	0	47%	100%	Technical limits	Standard with CCS	-42%	200	Oil: high Gas: medium Coall: low

Scenarios		***Scope***					***Results***				***Key assumptions***				
Reference	***Scenario-ID***	***GHG coverage***	***GEO***	***Base year***	***Coverage of relevant NIR emissions***	***GHG emissions in 1990 (Mt CO_2eq.)***	***GHG emissions in 2030 (Mt CO_2)***	***GHG emissions in 2050 (Mt CO_2)***	***GHG reduction in 2030 vs. 1990***	***GHG reduction in 2050 vs. 1990***	***Rationale behind GHG reduction***	***Technology***	***Production in 2050 vs. 2010***	***Carbon price in 2050***	***Energy prices***
Van Ruijven et al. (2016)	Baseline	CO_2 only	Global	2010	n.a	n.a	n.a	2750	n.a	n.a	Economics	Standard	n.a	n.a	n.a
Van Ruijven et al. (2016)	20$ / tCO_2	CO_2 only	Global	2010	n.a	n.a	n.a	2000	n.a	n.a	Economics	Standard	n.a	€ 65	n.a
Van Ruijven et al. (2016)	50$ / tCO_2	CO_2 only	Global	2010	n.a	n.a	n.a	2000	n.a	n.a	Economics	Standard	n.a	€ 162	n.a
Van Ruijven et al. (2016)	100$ / tCO_2	CO_2 only	Global	2010	n.a	n.a	n.a	1700	n.a	n.a	Economics	Standard	n.a	€ 324	n.a
Van Ruijven et al. (2016)	20$ / tCO_2 - with CCS	CO_2 only	Global	2010	n.a	n.a	n.a	950	n.a	n.a	Economics	Standard with CCS	n.a	€ 65	n.a
Van Ruijven et al. (2016)	50$ / tCO_2 - with CCS	CO_2 only	Global	2010	n.a	n.a	n.a	600	n.a	n.a	Economics	Standard with CCS	n.a	€ 162	n.a

Scenarios		***Scope***					***Results***				***Key assumptions***				
Reference	***Scenario-ID***	***GHG coverage***	***GEO***	***Base year***	***Coverage of relevant NIR emissions***	***GHG emissions in 1990 (Mt CO_2eq.)***	***GHG emissions in 2030 (Mt CO_2)***	***GHG emissions in 2050 (Mt CO_2)***	***GHG reduction in 2030 vs. 1990***	***GHG reduction in 2050 vs. 1990***	***Rationale behind GHG reduction***	***Technology***	***Production in 2050 vs. 2010***	***Carbon price in 2050***	***Energy prices***
Van Ruijven et al. (2016)	100$ / tCO_2 - with CCS	CO_2 only	Global	2010	n.a	n.a	n.a	500	n.a	n.a	Economics	Standard with CCS	n.a	€ 324	n.a
Wyns & Axelson (2016)	No scenario	CO_2 only	EU28	1990	n.a	164	n.a	295	n.a	80%	Technical limits	Breakthrough with CCS	n.a	n.a	n.a
CEMBUREAU (2013)	Max abatement without breakthrough technologies	CO_2 only	EU27	1990	n.a	157	n.a	112	n.a	29%	Technical limits	Standard	0%	n.a	n.a
CEMBUREAU (2013)	Max abatement with breakthrough technologies	CO_2 only	EU27	1990	n.a.	157	n.a	33	n.a	79%	Technical limits	Breakthrough with CCS	0%	n.a	n.a

Scenarios		***Scope***					***Results***				***Key assumptions***				
Reference	***Scenario-ID***	***GHG coverage***	***GEO***	***Base year***	***Coverage of relevant NIR emissions***	***GHG emissions in 1990 (Mt CO_2eq.)***	***GHG emissions in 2030 (Mt CO_2)***	***GHG emissions in 2050 (Mt CO_2)***	***GHG reduction in 2030 vs. 1990***	***GHG reduction in 2050 vs. 1990***	***Rationale behind GHG reduction***	***Technology***	***Production in 2050 vs. 2010***	***Carbon price in 2050***	***Energy prices***
UBA (2014)	THGND	All GHGs included	DE	2010	100%	24	n.a.	6	n.a.	74%	Technical limits	Breakthrough without CCS	0%	n.a.	n.a.
DECC (2015)*	BAU	CO_2 only	UK	2012	n.a.	n.a.	n.a.	7	n.a.	n.a.	Economics	Standard	0%	n.a.	n.a.
DECC (2015)*	Max. technology without CCS	CO_2 only	UK	2012	n.a.	n.a.	n.a.	5	n.a.	n.a.	Technical limits	Breakthrough without CCS	0%	n.a.	n.a.
DECC (2015)*	Max. technology with CCS	CO_2 only	UK	2012	n.a.	n.a.	n.a.	3	n.a.	n.a.	Technical limits	Breakthrough with CCS	0%	n.a.	n.a.
IEA (2009)	Baseline with high demand	CO_2 only	Global	2006	n.a	n.a	n.a	2796	n.a	n.a	Technical limits	Standard	n.a	n.a	n.a
IEA (2009)	Roadmap with high demand	CO_2 only	Global	2006	n.a	n.a	n.a	2521	n.a	n.a	Technical limits	Standard	n.a	n.a	n.a

Scenarios		***Scope***					***Results***				***Key assumptions***				
Reference	***Scenario-ID***	***GHG coverage***	***GEO***	***Base year***	***Coverage of relevant NIR emissions***	***GHG emissions in 1990 (Mt CO_2eq.)***	***GHG emissions in 2030 (Mt CO_2)***	***GHG emissions in 2050 (Mt CO_2)***	***GHG reduction in 2030 vs. 1990***	***GHG reduction in 2050 vs. 1990***	***Rationale behind GHG reduction***	***Technology***	***Production in 2050 vs. 2010***	***Carbon price in 2050***	***Energy prices***
IEA (2009)	Baseline with low demand	CO_2 only	Global	2006	n.a	n.a	n.a	2337	n.a	n.a	Technical limits	Standard	n.a	n.a	n.a
IEA (2009)	Roadmap with low demand	CO_2 only	Global	2006	n.a	n.a	n.a	2052	n.a	n.a	Technical limits	Standard with CCS	n.a	n.a	n.a
IEA (2009)	Roadmap with low demand with CCS	CO_2 only	Global	2006	n.a	n.a	n.a	1558	n.a	n.a	Technical limits	Standard with CCS	n.a	n.a	n.a
IEA (2009)	Roadmap with high demand with CCS	CO_2 only	Global	2006	n.a	n.a	n.a	1548	n.a	n.a	Technical limits	Standard with CCS	n.a	n.a	n.a
Non-metallic minerals (Ceramics)															
Ceramie-Unie (2013)	Scenario without electrification of kilns	CO_2 only	EU27	1990	n.a	22	15,5	9	30%	59%	Technical limits	Breakthrough with CCS	n.a	n.a	n.a

Scenarios		***Scope***					***Results***				***Key assumptions***				
Reference	***Scenario-ID***	***GHG coverage***	***GEO***	***Base year***	***Coverage of relevant NIR emissions***	***GHG emissions in 1990 (Mt CO$_2$eq.)***	***GHG emissions in 2030 (Mt CO$_2$)***	***GHG emissions in 2050 (Mt CO$_2$)***	***GHG reduction in 2030 vs. 1990***	***GHG reduction in 2050 vs. 1990***	***Rationale behind GHG reduction***	***Technology***	***Production in 2050 vs. 2010***	***Carbon price in 2050***	***Energy prices***
Ceramie-Unie (2013)	Scenario with electrification of kilns	CO$_2$ only	EU27	1990	n.a	22	15,5	5	30%	77%	Technical limits	Breakthrough with CCS	n.a	n.a	n.a
DECC (2015)*	BAU	CO$_2$ only	UK	2012	n.a.	n.a.	n.a.	1	n.a.	n.a.	Economics	Standard	n.a.	n.a.	n.a.
DECC (2015)*	Max. technology	CO$_2$ only	UK	2012	n.a.	n.a.	n.a.	1	n.a.	n.a.	Technical limits	Breakthrough with CCS	n.a.	n.a.	n.a.
Non-metallic minerals (Lime)															
UBA (2014)	THGND	All GHGs included	DE	2010	100%	9	n.a.	4	n.a.	61%	Technical limits	Breakthrough without CCS	-30%	n.a.	n.a.
ECOFYS (2014)	No scenario	CO$_2$ only	EU28	2010	n.a	n.a	23	18	n.a	n.a	Technical limits	Standard	n.a	n.a	n.a
Non-ferrous metals (Aluminium)															

Scenarios		***Scope***					***Results***				***Key assumptions***				
Reference	***Scenario-ID***	***GHG coverage***	***GEO***	***Base year***	***Coverage of relevant NIR emissions***	***GHG emissions in 1990 (Mt CO_2eq.)***	***GHG emissions in 2030 (Mt CO_2)***	***GHG emissions in 2050 (Mt CO_2)***	***GHG reduction in 2030 vs. 1990***	***GHG reduction in 2050 vs. 1990***	***Rationale behind GHG reduction***	***Technology***	***Production in 2050 vs. 2010***	***Carbon price in 2050***	***Energy prices***
UBA (2014)	THGND	All GHGs included	DE	2010	100%	14,6	n.a.	0	n.a.	100%	Technical limits	Breakthrough without CCS	25%	n.a.	n.a.
BMUB (2015)	EMS (2012)	All GHGs included	DE	1990	100% (42%)	2 (1)	1	0	53%	60%	Policies and measures	Standard	19%	50	Oil: high Gas: medium Coal: low
BMUB (2015)	CS 80	All GHGs included	DE	1990	100% (42%)	2 (1)	1	0	53%	60%	Policies and measures	Standard	19%	130	Oil: high Gas: medium Coal: low
BMUB (2015)	CS 95	All GHGs included	DE	1990	100% (42%)	2 (1)	0	0	57%	66%	Technical limits	Standard with CCS	16%	200	Oil: high Gas: medium Coal: low

Scenarios		***Scope***					***Results***				***Key assumptions***				
Reference	***Scenario-ID***	***GHG coverage***	***GEO***	***Base year***	***Coverage of relevant NIR emissions***	***GHG emissions in 1990 (Mt CO_2eq.)***	***GHG emissions in 2030 (Mt CO_2)***	***GHG emissions in 2050 (Mt CO_2)***	***GHG reduction in 2030 vs. 1990***	***GHG reduction in 2050 vs. 1990***	***Rationale behind GHG reduction***	***Technology***	***Production in 2050 vs. 2010***	***Carbon price in 2050***	***Energy prices***
EAA (2012)	No scenario	CO_2, PFCs	EU27	1990	n.a	32	16	22	52%	31%	Technical limits	Breakthrough	n.a	n.a	n.a

4.3 NIR GHG coverage of the studies

Table 46: NIR category coverage of the different studies

Study reference	GHG emissions covered according to NIR
COM 2011 Low-carbon roadmap and impact assessment	Manufacturing industries and construction emissions from fuel combustion plus industrial processes emissions for non-metallic minerals, chemicals and metal industry
ISI 2012 Energy efficiency for climate protection	Manufacturing industries and construction emissions from fuel combustion plus industrial processes emissions for non-metallic minerals, chemicals and metal industry
ISI 2014 Energy efficiency/saving potentials until 2020 and beyond	Manufacturing industries and construction emissions from fuel combustion plus industrial processes emissions for non-metallic minerals, chemicals and metal industry
BMUB 2015	In study all categories included, sector-differentiated presentation for process emissions only
BCG 2013 Steel's contribution to low-carbon Europe	Emissions from fuel combustion plus industrial processes emissions for the iron and steel sector
JRC 2012	Emissions from fuel combustion plus industrial processes emissions for the iron and steel sector
EUROFER 2013 Steel low-carbon roadmap	See BCG
van Ruijven et al. 2016 steel	n.a.
UBA 2014 THGND	All categories included
CEMBUREAU 2013 Cement low-carbon roadmap	n.a.
IEA 2009	n.a.
Ceramie-Unie 2013	n.a.
Ecofys Lime low carbon roadmap	n.a.
CEPI 2011 Pulp and paper low-carbon roadmap	Emissions from fuel combustion for pulp, paper, and print
EAA 2012 Aluminium low-carbon roadmap	n.a.
CEFIC 2013 Chemistry future	Emissions from fuel combustion plus industrial processes emissions for the chemical sector

4.4 Technology tables

The last column cites studies that included the specific technology in their analyses. If specific information is given which is only mentioned in one study, this is indicated by that study’s abbreviation next to the information.

We first present the existing technologies followed by efficiency measures and process optimisation. Subsequently, we describe innovative technologies.

In some studies, it was difficult to obtain detailed information on which technologies or measures are included in the estimated emission development/reduction potential. This refers in particular to the

BMUB 2015 study. Efficiency measures and process optimisation are certainly included to a large degree, but the study itself does not present detailed information and it would be time-consuming and tedious work to try and obtain that information.

4.4.1 Iron & Steel Industry

4.4.1.1 Currently available technologies

Table 47: Currently available technologies – Iron & Steel industry

Technology	Short description	CO2 saving potential/CO2 intensity	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
Main steel making processes						
Blast Furnace Route						
BF – BOF (Blast Furnace converter)	Iron ores in the form of lump ores, pellets or sinter are reduced in blast furnaces to produce iron using predominantly coal and coke as reducing agents. The hot metal is then converted into steel in the basic oxygen furnace	(BCG) Saving potential for BF-BOF not explicitly stated in study; (BCG, p. 11) CO_2 intensity in 2010: 1 888 kg CO_2/t crude steel (CS). (DECC) retrofitting option – 20% reduction in emissions	Commercially available (BCG) Accounted for 60% of 2010 EU production	Self-sufficient, no additional energy is needed due to use of waste gases (+) Mature technology, most of the plants in the EU are working close to optimum efficiency, thus there is limited scope for improvement (-) Usage of by-product slag in cement industry results in CO_2 reduction, reduced BF-BOF production could limit this abatement option in cement production(+) Most energy-intensive processes should be replaced by low-carbon technologies to reach max. abatement. Replacement of all BF – BOF plants is not economically viable	(BCG, p22) Operating expenses (OPEX): 429 €/t CS including 76% input factor costs 24% other OPEX Capital expenditures (CAPEX): 442 €/t CS for greenfield investment including 128 €/t CS BOF 149 €/t CS BF 51 €/t CS sinter plant 114 €/t CS coke plant 170 €/t CS for retrofit including: 64 €/t CS BOF (50% greenfield investment) 74 €/t CS BF (50% of greenfield investment)	BCG, EUROFER, van Ruijven et al. , BMUB, DECC

Technology	Short description	CO2 saving potential/CO2 intensity	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
				unless high CO_2 prices offset the cost of replacement (-).	15 €/t CS sinter plant (30% of greenfield investment) 17 €/t CS coke plant (15% of greenfield investment) (DECC) £100,000,000 per site	
SR – BOF (Smelting reduction converter) Finex (fine ores / fluidized bed pre-reduction)	Iron ores pre-reduced using off-gases from the melter-gasifier. Then pre-reduced iron ores are melted in the gasifier using coal as reducing agent. In the final stage, the hot metal is charged to a BOF. The process gas can be used to produce electricity	(BCG, p. 31) higher CO_2 intensity than BF-BOF.	Commercially available No information about current EU usage; worldwide 11 plants operate with Corex and Finex processes, producing ~ 7mt of hot metal (2014)[12] process is restricted to particular regions and plant configurations for cost reasons[13]	Higher CO_2 intensity but reduced particle production (NOx, SOx) and waste water emissions (-, +) Greatest reduction potential with CCUS due to the higher CO_2 content; it is easier to separate, store and use (+) lower production performance than large blast furnace[14]	(BCG, p22) OPEX: 440 €/t CS including 82% input factor costs 18% other OPEX (CAPEX): 393 € / tCS including 265 €/t CS 128 €/t CS BOF with 50% greenfield invest. (JRC) Investment cost: 460 M€ for 2 Mt/year capacity	BCG, JRC, EUROFER, DECC
SR – BOF Corex (lump ores, pellets	Lump iron ore or pellets are reduced	(BCG, p. 31)	see previous row on Finex[15]	Higher CO_2 intensity compared to other processes, but reduced	(JRC) Investment cost:	BCG, JRC, EUROFER,

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[12] http://en.stahl-online.de/index.php/estad-europes-largest-technical-steel-conference-in-duesseldorf/

[13] http://en.stahl-online.de/index.php/topics/technology/steelmaking/

[14] ebid

[15] ebid

Technology	Short description	CO2 saving potential/CO2 intensity	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
/ shaft pre-reduction)	directly by the reducing gas from melter-gasifier. The top gas leaving from the shaft is partly recycled	Substantially higher CO_2 intensity than BF-BOF (and even 20% higher than Finex		particle production (NOx, SOx) and waste water emissions (-, +) Greatest reduction potential with CCUS due to the higher CO_2 content, which makes it easier to separate, store and use (+) lower production performance than large blast furnace[16]	460 M€ for 2 Mt/year capacity	van Ruijven et al., DECC
Electric Arc Furnace Route						
DRI – EAF (direct reduced–iron, further processed in electric arc furnace) Midrex and HYL; for lump ores or pellets reduced in a shaft Finmet, Circored; Fine ores reduced in fluidized bed	Oxygen from iron ore is removed by a chemical reaction with a hot reducing gas instead of being melted. Iron is then fed into the electric furnace	(BCG, p. 17, 20) specific emissions: 1.2t CO_2/t (with natural gas in DRI).	Commercially available worldwide (70 million tonnes of DRI in 2011, BCG p. 10), however only one plant exists in EU with an annual production of around 0.45 Mt (BCG, p. 8)	Less emission intensive (+) Hot charging of DRI enables higher savings (+) Allows better storage and transportation of pyrophoric material (+) (BCG) Based on reduction of pellets. The pellets are mainly produced outside EU, thus increase in production via DRI – EAF might mean closure of sinter plants in EU and create an upstream emission burden of 105 kg CO_2/t pellet (-) (UBA) allows almost complete reduction of GHG emissions from steel production if	(BCG, p22) Based on Midrex technology OPEX: 572 € / tCS including 87% input factor costs 13% other OPEX CAPEX: 414 € / tCS including 184 €/tCS EAF 230 €/tCS DRI (JRC) Investment cost: Midrex: 250 M€ for 1 Mt/year capacity HYL: 350 M€ for 2 Mt/year capacity	BCG, JRC, EUROFER, van Ruijven et al. 2016, DECC, UBA

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[16] ebid

Technology	Short description	CO2 saving potential/CO2 intensity	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
				combined with hydrogen instead of natural gas (+)		
Scrap – EAF	Ferrous scrap directly fed into the electric arc furnace to be melted Half of the emissions are indirect emissions from purchased electricity.	(BCG, p. 16) Specific emissions: 455kg/t (2010) 341 kg/ t (2050) reduction largely driven by decrease in CO_2 factor of electricity (429 g/kWh (2010), 210 g/kWh (2050)	Commercially available (BCG, p. 40) covers around 41% of total EU production	least emission-intensive process (+) depends on scrap availability (-) scrap quality s a limiting factor (-) upper limit in production share is (BCG) 44%, (JRC) 47% of the whole production due to the above restrictions (-) indirect emissions are reduced as long as the power sector is decarbonizing (+) US shale gas production and unsustainable energy prices in Europe prevent EAF process from further expansion (-)	(BCG, p22) OPEX; 489 €/tCS including 88% input factor costs 12% other OPEX CAPEX: 184 €/tCS for EAF	BCG, JRC, EUROFER, van Ruijven et al. 2016, DECC, UBA, BMUB
Efficiency measures and process optimisation in steel making						
Heat recovery and re-use in all plants: conventional options	On-site power generation, steam generation or pre-heating of raw material or integration in local district heating network	(DECC, p. 67, appendix) 1% CO_2 emission reduction	Commercially available 50% applied in UK plants	n.a.	CAPEX: £1,000,000 per site	DECC

Technology	Short description	CO2 saving potential/CO2 intensity	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
Sinter plant cooling heat recovery	Recover energy from the sintering process by returning the exhaust gas from the sinter bed as combustion air or from hot sinter ore at the end of sinter bed using a sintered ore cooling system	(BCG, p28) 13 kg CO_2 / t CS (JRC) 27 kg CO_2 / t sinter ore	Commercially available (BCG, p. 28) currently used in 12 of 53 sinter plants in EU	Feasible in any scenario (+)	(JRC) investment cost: 6 M€ for 1.8 Mt/year capacity	BCG, JRC, CS-IS
Coke dry quenching	Recovering some thermal energy during the cooling of hot coke with gas to produce electricity	(BCG, p28) 18 kg CO_2 / t CS (JRC, 18) 83 kg CO_2 / t coke (total emission reduction) 10 kg CO2 / t coke (direct emission reduction) (DECC) 5% CO_2 emission reduction	Commercially available (BCG, p. 29) currently used in 10% of coke production in EU	Low effect due to limited use of coke and decarbonization of energy sector (-) Feasible in a scenario where the input factor prices are five times higher in 2050	(JRC) Investment cost: 69 M€ for 1.5 Mt / year capacity (DECC) capex: £46,500,000 per site	BCG, JRC, DECC
Fuel substitution: coking plant	Using waste plastics or equivalent in the coke oven	10% CO_2 emission reduction	Commercially available Not yet adopted in UK	n.a	Capex: £750,000 per site	DECC

Technology	Short description	CO2 saving potential/CO2 intensity	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
Blast Furnace - Top Gas Recovery Turbine (TRT)	Electricity generation using the top gas pressure of the furnace	(BCG, p. 28) 9 kg CO_2 / t CS (JRC, p18) 14 kg CO_2 / t product	Commercially available (JRC, p. 17) 22 TRTs currently installed in the EU	incompatible with TGR–BF (see under 5.4.1.2 Innovative technologies) (-); feasible in any scenario (+); abatement potential decreases with declining CO_2 intensity of the power sector	(JRC) Investment cost: 9 M€ for 3 Mt/year capacity	BCG, JRC, DECC
BOF Waste Heat and Gas Recovery	Making high pressure steam or fuel to replace natural gas in other parts of the installation from process gas released in BOF during conversion of hot metal into liquid steel	(BCG, p28) 23 kg CO_2/t liquid steel, 24 kg CO_2/ t CS. (JRC) 51 kg CO_2 / t product (DECC) 5% CO_2 emission reduction	Commercially available (BCG) currently used in 70% of the plants in EU. Target to increase usage to 100% is feasible (DECC) 30% of UK plants adopted	n.a	(JRC) Investment cost: 37.5 M€ for 2.8 Mt/year capacity (DECC) capex: £35,000,000 per site	BCG, JRC, DECC
Stove Waste Gas Heat Recovery	Improve efficiency of hot blast stoves by recovering waste gas and using it to pre-heat BF-gas and/or combustion air	(JRC, p18) 15 kg CO_2 / t product (DECC) 8% CO_2 emission reduction	(JRC) 18 stove waste gas heat recoveries currently installed in the EU (DECC) Not realized in UK	n.a	(JRC) Estimated Investment cost: 3.7 M€ for 1.5 Mt/year (DECC) £13,500,000 per site	JRC, DECC
Waste heat recovery from sintering	Recovering heat from machine exhaust and sinter cooler off-air to	25% CO_2 emission reduction	Commercially available	n.a	Capex: £5,000,000 per site	DECC

Technology	Short description	CO2 saving potential/CO2 intensity	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
	produce electricity using steam or to use steam in the process. Excess heat can be recirculated to the processes or used to preheat combustion air in the ignition hood or to pre-heat sinter mix or for district heating					
Scrap pre-heating	Using waste heat of furnace to preheat the incoming scrap charge	37 kg CO_2 / t scrap	Commercially available: 99 scrap pre-heating systems operating in the EU	possible formation of undesired organic compounds such as dioxins or furanes (- -) Pre-treatment of scrap can partially avoid these effects[17]	Estimated investment cost: 2.3 M€ for 0.5 Mt/year capacity	JRC
Heat recovery from cooling water	Heat from spraying water to cool the rolled steel can be recovered and low pressure steam can be produced with an absorption heat pump	Less than 1% emission reduction	Commercially available No adoption in UK	n.a	Capex: £26,300,000 per site	DECC

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[17] http://www.google.ch/patents/WO2011141036A1?cl=de

Technology	Short description	CO2 saving potential/CO2 intensity	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
Injection of natural gas or coke oven gas (COG) as H_2 rich reductant	Using high H_2 or H_2-rich gases to reduce material use	(BCG, p. 28) 85 kg CO_2 / t CS	Commercially available No information about EU usage	COG is being used in other processes, substitution may result in more emissions (-) Depends on the layout of the steel mill (-)	n.a	BCG
Optimisation of pellet ratio in BF - BOF	100% pellets based BF - BOF	(BCG, p28) 119 kg CO_2 / t CS	Commercially available However, only used in small facilities 8% of hot metal production is based on 100% pellet	Need for alternatives to handle iron, carbon and flux containing residues currently recycled in sinter plants (-)	n.a	BCG
Optimised sinter pellet ratio	Achieve a sinter-pellet ratio of at least 50/50 for each blast furnace	(JRC, p18) 35 kg CO_2 / t iron ore	Commercially available Not currently implemented in any plants in EU according to JRC (p. 17)	n.a	n.a	JRC
Oxy-fuel burners	Use oxygen-fuel burners in EAF to provide chemical energy to cold-spots, making heating the steel more uniform	(JRC, p18) 6 kg CO_2 / t product (total emission reduction)	Commercially available: 136 oxy-fuel Burners are currently installed in the EU	n.a	Estimated investment cost: 2.8 M€ for 0.5 Mt/year capacity	JRC
Pulverised Coal Injection (PCI)	Injecting coal into blast furnaces.	(JRC, p18)	Commercially available. JRC stated	n.a	(JRC) Estimated investment cost:	JRC, CS-IS, DECC

Technology	Short description	CO2 saving potential/CO2 intensity	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
	Savings relate to the production of coke rather than the effect in the process	21 kg CO_2 / t hot metal (total emissions) 26 kg CO_2 / t CS hot metal (direct emissions) (DECC) 5% CO_2 emission reduction	there were no PCIs in stalled in the EU. Some exist today, e.g. Arcelor Mittal in Eisenhüttenstadt[18]in Germany or Redcar in the UK[19]		57 M€ for 10 Mt/year capacity (DECC) capex: £45,000,000 per site	
State-of-the-art power plant (steam boiler plus turbine)	A power plant on site or near to the production plant where process-related gases are used to produce power and steam. Replacement of the older power plants with best practice (32% conversion efficiency)	(JRC, p18) 442 kg CO_2 / t CS	Commercially available: (JRC, p16) No best practice installation with that efficiency rate (32%) in EU	n.a	Estimated investment cost: 70 M€ for 100 MWe	JRC
EAF – process optimisation	Improve below processes on EAF; control of chemical energy output	(BCG, p28) 20 kg CO_2 / t CS	Commercially available 50% of UK plants realized	Feasible to apply to all EAF plants (+)	(DECC) capex: £1,500,000 per site	BCG, DECC

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[18] http://www.arcelormittal-ehst.com/produktion/metallurgischer+zyklus/roheisen-+erzeugung?start=4&pgnr=5&lang=de

[19] http://www.siemens.com/press/de/pressemitteilungen/?press=/de/pressemitteilungen/2012/industry/metals-technologies/imt201205022.htm&content[]=IMT&content[]=PDMT

Technology	Short description	CO2 saving potential/CO2 intensity	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
	post combustion process in EAF continuous online monitoring of energy balance end point control of EAF tapping temperature					
Scrap densification or shredding	Improved density of scrap leads to improved efficiency of heat	5% electricity consumption reduction	Commercially available 35% of UK plants realized		capex: £1,000,000 per site	DECC
Ultra High Power (UHP) transformers	Converting furnace operation to UHP reduces energy losses and increases productivity	5% electricity consumption reduction	Commercially available 33% of UK plants realized		capex: £1,750,000 per site	DECC
Energy efficiency improvements through ICT	automation and computerization of rolling mills	n.a	n.a.	n.a	n.a	CS-IS
Resource efficiency	Reducing material losses in the production process, improving the recycling rate	n.a.	n.a	n.a.	n.a.	UBA

Technology	**Short description**	**CO2 saving potential/CO2 intensity**	**Status**	**Advantages (+) / restrictions (-), according to the respective study**	**Cost of the technology**	**Included in the studies**
Material efficiency	Creating lightweight steel design, improving yield ratios along the supply chain, reusing components, diverting manufacturing scrap to avoid high melting energy	20-25% reduction in material usage with a combination of different approaches	n.a	Nature of downstream sectors like construction can be less open to uptake of material efficiency (-) Might not be economically feasible (-)	n.a	CS IS, UBA
Shortening process chains	Shorter production chains can increase energy efficiency in particular by reducing heat losses. One option is near-net-shape casting.	n.a.	n.a.	n.a.	n.a.	UBA
Improved automation and process control and installing VSDs on electrical motors (pumps and fans)	Realizing set point for the flow rate by changing the rotation speed of the motor	n.a	Commercially available More than 50% realized in UK plants		Capex: £4,270,000 per site for VSDs £750,000 for improved automation	DECC
Reducing yield losses	Avoiding off-spec products and	3% CO_2 emission reduction	Commercially available	n.a	Capex: £500,000 per site	DECC

Technology	Short description	CO2 saving potential/CO2 intensity	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
	reducing yield losses		40% realized in UK plants			
Compressed air system optimisation	Measures like; compressed air pressure reduction, leak detection and remediation, avoiding unnecessary use, optimising dew point setting, improved compressor control	3% reduction in electricity consumption	Commercially available 34% realized in UK plants	n.a	Capex: £750,000 per site	DECC
Use of premium efficiency electrical motors	Using premium efficiency motors when replacing large electrical motors with high duty factor	10% reduction in electricity consumption	Commercially available 32% realized in UK plants	n.a	Capex: £4,000,000 per site	DECC
Steam or power production system optimisation	Measures like: blowdown optimisation, feed water quality optimisation, improved boiler cleaning procedures, oxygen tuning, flue gas	n.a	Commercially available 13% realized in UK plants	n.a	Capex: £50,000,000 per site	DECC

Technology	Short description	CO2 saving potential/CO2 intensity	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
	heat recovery, feed water pre-heating, VSDs on feed water pumps, condensate return optimisation, improved insulation, optimising control of multiple boilers					
Improved site or integration of different sectors	Ecopond, industry park or complex, heat integration, BF slag use in cement, waste gas integration	15% CO_2 emission reduction	Commercially available 10% realized in UK	n.a	Capex: £400,000,000 per applicable site	DECC
Hot charging	Charging slabs at high temperatures in the reheating furnaces	3% CO_2 emission reduction	Commercially available, 3% adoption in UK	Energy saving (+) Improves material quality (+) Reduce material loss (+) Enhance material productivity (+)	Capex: £26,300,000 per site	DECC
Improved planning and throughput optimisation: secondary processes	Utilization of the process	5% CO_2 emission reduction	Commercially available, 12% adoption in UK	Reduces heat losses (+) Better utilization of milling capacity (+) Avoids overcapacity and reduces energy consumption as a result (+)	Capex: £350,000 per site	DECC

Technology	Short description	CO2 saving potential/CO2 intensity	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
Re-heating furnace optimisation	Optimisations in re-heating process	Reduction in fuel consumption	Commercially available, 19% adoption in UK	n.a	Capex: £1,500,000 per site	DECC
Near net shape casting - Thin Slab Casting (TSC) and Strip Casting (SC); Castrip® process	Casting to form and dimensions close to finished product TSC: cast directly to slabs of 30 - 60 mm thickness instead of 120 - 300 mm SC: direct casting of thin strip from liquid steel (0.8 - 2.0 mm)	58% CO_2 emission reduction	Commercially available, 10% adoption in UK	Cannot be realized in all processes (-)	Capex: £150,000,000 per site	DECC
Endless strip production	New development of thin slag casting and direct rolling	40% CO_2 emission reduction	Commercially available, no adoption in UK	Reduction of consumables (+) Improved yield (+)	Capex: £30,000,000 per site	DECC
Regenerative or recuperative burners: secondary processes	Regenerative burners have heat reservoirs to recover heat, recuperative burners use gas heat exchangers or gas to recover furnace heat by preheating combustion air	Reduction in fuel consumption	Commercially available, 54% adoption in UK	n.a	Capex: £4,270,000 per site	DECC

Technology	Short description	CO2 saving potential/CO2 intensity	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
Restructuring						
Fuel shift from coal to gas & electricity	Using DRI/EAF or scrap EAF processes instead of BF/BOF	n.a	n.a	Quality of scrap is decreasing, although quantity increasing (-) DRI process is gas intensive. Gas imports will increase with increase in DRI production in Europe, (-) EAF depends on electricity prices In order to shift through DRI/EAF processes, high carbon prices needed to compensate high EU gas prices (-) Also enables hydrogen use instead of fossil fuels	n.a	CS-IS, UBA, van Ruijven et al.

4.4.1.2 Innovative technologies

Table 48: Innovative technologies – Iron & Steel industry

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
Heat recovery and re-use in all plants: innovative options	Heat recovery by organic ranking cycle, kalina cycle (converts thermal energy into usable mechanical power)	(DECC p. 69, appendix) 1% CO_2 emission reduction	Validated in industry environment but no pilot yet	n.a	CAPEX: £1,000,000 per site	DECC

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
	or thermophotovoltaic (TPV) conversion (direct conversion of radiation heat to electricity)					
TGR – BF (top gas recycling blast furnace) with and without CCS	Recycle a part of blast furnace gas (CO and H_2 rich) and use as reducing agent instead of coke or coal. Captured CO_2 is stored geologically	(BCG, p. 28) 189 kg CO_2 / t CS without CCS; (JRC, p20) 325 kg CO_2 / t hot metal without CCS; (EUROFER, Wyns and Axelson) 15% per t CS without CCS, 60% with CCS ; (CS IS) 25% CO_2 per t steel, with CCS 75%	Pilot (JRC) Deployment 2020 (BCG) Estimated to be commercial 2035	Great potential with CCUS (+) High investment costs (-)	(JRC) Investment cost: 100 M€ for 2 Mt/year capacity (CS IS) €300 – €400 million with CCS (EUROFER) €50 / t CO_2 for carbon capture without the costs for storage and transportation	BCG, JRC, EUROFER, CS IS, Wyns and Axelson, DECC
Electrolysis (Part of ULCOS program) - ULCOLYSIS & ULCOWIN	Using electrolysis for iron making	(CS IS) 100% direct CO_2 reduction/ t steel Total reduction depends on carbon intensity of power sector (EUROFER) 30% with today's energy mix	R&D (JRC) deployment 2040 onwards	Heavily dependent on electricity (-) Feasible if the power sector becomes CO_2-free (+) Generate off-gas which can be sold for profit (+)	n.a	BCG (but not incl. in calculations), JRC, CS IS, Wyns and Axelson, UBA

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
		60% with CO_2-free electricity generation				
Direct Sheet Plant (DSP)	Full integration of casting and rolling processes eliminates the need for cooling, reheating, handling and transportation of slabs	(JRC, p20) 73 kg CO_2 / t finished product (total emission reduction) 68 kg CO_2 / t finished product (direct emission reduction)	n.a	n.a	Estimated investment cost: 250 M€ for 2 Mt/year capacity	JRC, UBA
DRI – EAF ULCORED (Part of ULCOS program)	Making iron based on direct reduction using natural gas as reduction agent rather than coal or coke and separating CO_2 from the process gas and storing it	(JRC) 907 kg CO_2 / t DRI. (EUROFER, Wyns and Axelson) 5% reduction in specific emissions without CCS 80% reduction in specific emissions with CCS. (CS IS) Up to 50% reduction in specific emissions (CO_2/t steel).	(EUROFER) Awaiting pilot (JRC) deployment 2020 onwards	Not very suitable for Europe due to the natural gas prices (-)	(JRC) Investment cost: 250 M€ for 1 Mt/year capacity	BCG, JRC, EUROFER, CS IS, Wyns and Axelson, -
DRI – EAF with preferably hydrogen	Making iron based on direct reduction using preferably	(UBA, p. 146, 149) 10.5-12.5 GJ/t (DRI) + 2.11 GJ/t (EAF);	(Wyns and Axelson) Pilot project in	Direct avoidance of CO_2 by use of hydrogen (or renewable	n.a.	Wyns/Axelson UBA

Technology	**Short description**	**CO_2 saving potential**	**Status**	**Advantages (+) / restrictions (-), according to the respective study**	**Cost of the technology**	**Included in the studies**
(alternatively methane produced with renewable energy)	hydrogen or renewable methane as reduction agent rather than coal or coke or natural gas	total CO_2 emissions in Germany reduced by 99.7% vs 2010.	Sweden launched in April 2016[20]	methane) in the production process (+) Large amounts of hydrogen/renewable methane and hence electricity required (-)		
HIsarna (Part of ULCOS program)	Smelting reduction process concept incorporating a cyclone for heating and melting iron ore and a bath smelter to produce a CO_2-rich off-gas by using pure oxygen. Gas expected to be stored	(JRC, p. 20) 383 kg CO_2 / t iron ore (EUROFER, CS IS, Wyns and Axelson) (BCG, p. 31) Reduction of specific CO_2 emissions 20% without CCS 80% with CCS	Pilot (JRC) Deployment 2030 onwards (Wyns and Axelson) Full size demonstration to be operational between 2020-2025	Significantly less coal is needed (+) Process is more competitive with conventional processes and requires less capital outlay (+) Needs to be scaled up to commercial level (-)	(JRC) Investment cost: 100 M€ for 1 Mt/year capacity	BCG, JRC, EUROFER, CS IS, DECC
CCUS (Carbon capture and storage/use)	Carbon Capture and Storage/Utilization	Depends on the technology to which it is applied (BCG, p. 26) emission reduction up to nearly -60% compared to 1990	Different development stages (JRC) Deployment 2020 onwards (BCG, p. 26) full implementation in	Extremely important for higher reduction levels than in the min. scenario (+) Feasibility and economic viability depend on technological improvement and supporting policies (-)	(EUROFER) €30-€100 per tonne of CO_2 stored	BCG, JRC, EUROFER, van Ruijven at al., DECC

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[20] For projects by other firm consortia in the EU directed at this technology, see the industry slides presented on a stakeholder workshop organized by the European Commission on 17 February 2017: https://ec.europa.eu/clima/events/articles/0115_en, “17 February 2017: Workshop 1 ‘Ferrous and non-ferrous metals’ ”. For DRI-EAF with (fossil) methane see Table 47

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
		with full implementation of CCUS	2050 as very optimistic assumption. Availability not expected until around 2030 and a relatively long S-curve adaptation	Not every production process is equally suitable for CCUS Smelting reduction has the highest potential Any route with EAF has less potential because EAF process has no carbon capture opportunities Relative final specific CO_2 emissions of technologies with CCUS are similar BF–BOF and DRI–EAF 750 kg CO_2/tCS SR–BOF 700 kg CO_2 / tCS		
Pulverised coal injection with bio-charcoal	Use of bio-char coal instead of fossil coal	29% CO_2 emission reduction	Demonstration stage	n.a	n.a	DECC
Stove waste gas recycling with CC		27% CO_2 emission reduction	Demonstration stage	n.a	Capex: £17,000,000	DECC

4.4.2 Pulp and Paper Industry

4.4.2.1 Currently available technologies

Table 49: Currently available technologies – Pulp & Paper industry

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
Applying best available technologies	Capital stock turnover and consolidation; mills and machines, power and heat boilers, recovery boilers. Changing direct-fired infrared dryers in paper machines to electricity-based dryers	Capital stock turnover and consolidation; 25% reduction compared to 2010 emissions (10 $MtCO_2$ emission reduction) Infrared dryers (1-2 $MtCO_2$ emission reduction)	Currently applied	n.a	Capital stock turnover; in total € 260 bn until 2050	CEPI, UBA
Fuel mix change	Changing fuel from gas, coal, oil and peat to biomass, pellets, bio coal, pyrolysis, biogas. Use of CHP only in biomass/biogas applications (due to the decarbonisation of centralized power generation)	Fuel mix change 5–6 $MtCO_2$ emission reduction Biomass CHP 1-2 $MtCO_2$ emission reduction	n.a	n.a	n.a	CEPI, UBA
New products and services	Production of nanocellulose bio-composite materials, biofuels and bio-chemicals	n.a	Currently applied on a small scale	Too energy-intensive (-) With increase in demand, emerging technologies are needed to scale up production	n.a	CEPI

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
Increased recycling and better sorting	Increased use of recycled paper frees up more fibres for the sector (can also be used as an energy source), avoids methane landfill emissions and improves resource efficiency	n.a	All applied in Europe	Europe is nearly at the capacity limit (-)	n.a	CEPI, UBA
Efficiency measures and process optimisation across the paper mill						
(Waste) heat recovery and heat integration	Take a systematic approach to heat recovery with technologies like pinch or innovative heat recovery	9% CO_2 emission reduction	Commercially available 64% adopted in UK	n.a	Capex: £500,000-1,000,000 per site	DECC, UBA
Heat recovery technologies like Organic Rankine cycles, heat pumps	Heat recovery from the process by ORC or heat pumps	3% CO_2 emission reduction	Commercially available 8% adopted in UK	n.a	Capex: £500,000-1,000,000 per site	DECC
Better energy management and monitoring	Installing meters for steam, electricity, air and gas to allow online energy balances	15% CO_2 emission reduction	Commercially available 76% adopted in UK	n.a	Capex: £200,000-5,000,000 per site	DECC, UBA

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
Improved process control across the entire mill (process and utilities)	Optimised control of process takes into account all possible parameters which can influence the process	5% CO_2 emission reduction	Commercially available 42% adopted in UK	n.a	Capex: : £200,000-5,000,000 per site	DECC, UBA
Industrial clustering and heat networking	Using the waste heat from industry in district heating or industries with low heat demand	n.a	Commercially available	n.a	Capex: £2,000,000-7,000,000 per site	DECC, UBA
Focus on maintenance, replace lighting with high efficiency lighting	Regular maintenance programme for utilities, clean wires, felts and drying surfaces	10% CO_2 emission reduction and 3% electricity consumption reduction for lighting	Commercially available 8% adopted in UK	n.a	Capex: £0-200,000 per site	DECC, UBA
Efficiency improvements in fibre supply						
Efficient screening	Improvements in screening and filtering	15% reduction in electricity consumption	Commercially available 83% adopted in UK	n.a	Capex: £500,000-1,000,000 per site	DECC
High consistency pulping	Increase slurry consistency	8% reduction in electricity consumption	Commercially available 76% adopted in UK	Electricity demand of pulper can be reduced (+)	Capex: £2,000,000-7,000,000 per site	DECC
Sludge dryer	Use waste heat to pre-dry sludge before burning	8% reduction in electricity consumption	Commercially available	Increase the calorific value of sludge (+)	Capex: £500,000-1,000,000 per site	DECC

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
			12% adopted in UK			
Efficiency improvements in the paper machine						
Closed hood	Replacement of semi-open hoods with closed hoods	13% CO_2 emission reduction 45% reduction in electricity consumption	Commercially available 86% adopted in UK	n.a	Capex: £1,000,000-2,000,000 per paper machine	DECC, UBA
High consistency forming	Process pulp entering the forming stage with more than double the normal consistency	3% CO_2 emission reduction	Available in demonstration 15% adopted in UK	Increase forming speed (+) Reduces dewatering and vacuum power needs (+)	Capex: £2,000,000-7,000,000 per paper machine	DECC
Hot pressing	Increase solid content before entering the dryer	8% CO_2 emission reduction	Available in demonstration 1% adopted in UK	n.a	Capex: £500,000-1,000,000 per paper machine	DECC
Impulse drying	Applying heat and pressure to dewater before drying	20% CO_2 emission reduction	Commercially available Not yet adopted in UK	n.a	Capex: £2,000,000-7,000,000 per paper machine	DECC
Increase dew point in hood from 55°C to 70°C	Increase relative humidity	5% CO_2 emission reduction	Commercially available 63% adopted in UK	n.a	Capex: £200,000-5,000,000 per paper machine	DECC
Infrared profiling	Short-wave IR drying	5% CO_2 emission reduction	Commercially available	Better heat transfer capacities (+)	Capex: £200,000-	DECC

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
			9% adopted in UK	Improved energy efficiency (+) Increase drying power output (+)	5,000,000 per paper machine	
State of the art steam systems	Condensation system with stationary syphons and spoiler bars with optimised differential pressures for condensate evacuation	10% CO_2 emission reduction	Commercially available 76% adopted in UK	n.a	Capex: £200,000-5,000,000 per paper machine	DECC
Steam box	Increases the sheet temperature and dryness	5% CO_2 emission reduction	Commercially available 58% adopted in UK	n.a	Capex: £500,000-1,000,000 per paper machine	DECC
Use of flash steam from condensate		2% CO_2 emission reduction	Commercially available 35% adopted in UK	n.a	Capex: £200,000-5,000,000 per paper machine	DECC
Cross-cutting technologies/ utilities						
Compressed air (CA)	Optimisation of system pressure, avoid CA usage , instead use blower air, electric motors, etc.	Reduction in electricity consumption	Commercially available Different adoption level for different technologies in UK	n.a	Capex: £200,000-7,000,000 per paper machine	DECC

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
Pumps and motor systems	Optimise the design of the motor systems	15% reduction in electricity consumption	Commercially available 83% adopted in UK	n.a	Capex: £200,000-5,000,000 per paper machine	DECC
Water systems	Install anaerobic waste water treatment plant	2% CO_2 emission reduction	Commercially available 7% adopted in UK	n.a	Capex: £2,000,000-7,000,000 per paper machine	DECC
Steam system optimisation	Install economizer in steam boilers, optimise steam control turbine	2% - 8% CO_2 emission reduction	Commercially available 66% for steam control turbine, 78% for economizer adopted in UK	n.a	Capex: £200,000-5,000,000 per paper machine	DECC
Oxygen trim control to adjust burner inlet air (and detect air infiltration)	Optimise fuel/air mix for high flame temperature and leakage control	3% CO_2 emission reduction	Commercially available 70% adopted in UK	n.a	Capex: £0-200,000 per site	DECC
Local steam generators	Replacement of pressure reduction valves with local steam generators	n.a	Commercially available Not yet adopted in UK	n.a	Capex: £500,000-1,000,000 per paper machine	DECC
Biomass-based CHP or boiler	Gasification of biomass in gas turbine or in CHP	Zero emissions	Commercially available	n.a	Capex: £2,000,000-7,000,000 per paper machine	DECC

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
			19% for CHP adopted in UK, not yet adopted for gasification			

4.4.2.2 Innovative technologies

Table 50: Innovative technologies – Pulp & Paper industry

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
Improved efficiency in pulp production	Technologies for improving efficiency in refining and grinding for mechanical pulp production Pre-treatment of woodchips to reduce energy consumption	n.a	n.a	n.a	n.a	CEPI, UBA
Improved energy efficiency in paper making	Lowering heat demand of drying section of paper machines, layered sheet-forming, advanced fibrous fillers, highly	n.a	Some emerging technologies already partially applied	n.a	n.a	CEPI, UBA

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
	selective fractionation processes					
Black liquor gasification in pulp mills and the extraction of black liquor	Emerging thermochemical path for producing syngas Extracting lignin from pulping liquor to replace fossil fuel materials in any sector	n.a	Full scale investment expected after 2015 - 2020	No large gas turbine is interested so far (-)	n.a	CEPI,
Integrated bio-refinery complexes (e.g. pulp and paper mills with waste management and incineration facilities)	Combination of industries at a single site. Using the waste flows and/or the heat from municipal waste incinerators	n.a	Suggestion	n.a	n.a	CEPI
CCS and BECCS (Bio-Energy with Carbon Capture and Storage)	Capturing CO_2 from the processes where the biomass is used	n.a	Expected start in 2020-2025 and expected commercialization in 2030	Not included in this roadmap Valuation of negative CO_2 is needed The investment needed for the application can be directed to reducing the heat consumption with other breakthrough technologies	n.a	CEPI
Dry sheet forming	Dispersing fibres through carding	42% CO_2 emission reduction	Pilot	n.a	Capex: £2,000,000-	DECC

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
	(mechanical) or air laying techniques				7,000,000 per paper machine	
Shoe press technology and improved dewatering	Installing shoe press technology and improving dewatering in press section beyond shoe press	8% CO_2 emission reduction	R&D	High dewatering efficiency (+) Operating cost savings (+) Reduced energy consumption of drying (+)	Capex: £2,000,000-7,000,000 per paper machine	DECC
Two Team project from CEPI						
Deep eutectic solvents	Production of pulp at low temperatures and atmospheric pressures	20% CO_2 emission reduction	R&D	Any type of biomass with cellulose and hemi-cellulose can be dissolved	n.a	DECC
Dry pulp for cure-formed paper	Waterless pulp production	55% CO_2 emission reduction	R&D	n.a	n.a	DECC
Flash condensing with steam	Blasting of largely dry fibres into a forming zone with agitated steam and condensing into a web with minimum water	50% CO_2 emission reduction	R&D	n.a	n.a	DECC
Supercritical CO_2	Drying process requires no steam or heat	15% CO_2 emission reduction	R&D	n.a	n.a	DECC

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
Superheated steam drying	Using high temp. steam for drying, followed by fibre carrier and forming paper	50% CO_2 emission reduction		n.a	n.a	DECC

4.4.3 Chemical Industry

4.4.3.1 Currently available technologies

Table 51: Currently available technologies – Chemical industry

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
Bio-based chemicals						
Bio-based chemicals - general	Production of chemicals from bio-based feedstock such as starch, sugars, vegetable oils, animal fats or lignocellulosic material via fermentation, transesterification, thermo-chemical conversion or pyrolysis	Heavily dependent on which bio-feedstock is used, conversion technology and end product; it is assumed that average energy use of bio-mass routes will be similar to fossil fuel routes,	First generation feedstock (e.g. using bio-ethanol to produce polyethylene terephthalate bottles-commercialized Second generation feedstock – to be	Appropriate bio-feedstock use depends on desired product (-) Cost of bio-based production currently exceeds cost of petrochemical-based production (-) Producing syngas as a feedstock via thermo-chemical conversion is six times more expensive than conventional methods. To make the process economically viable, large differences between	Depends on bio-feedstock, conversion technology and endproduct. No detailed cost evaluation is given in the study (DECC) total cost for the UK sector: £ 10,000,000,000	CEFIC, DECC

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
		which is not the case currently	commercialized in 5 – 10 years	feedstocks (e.g. natural gas and woody biomass) are needed (-)		
Bio-based chemicals – ethylene by ethanol from bio-based inputs	Ethanol production from fermentation of sugar in crops (less favourable due to the land use conflicts), cellulosic ethanol conversion from forest residues or municipal solid waste (MSW) (more favourable)	n.a	Ethanol from cellulose is commercially available, but currently used as a biofuel not as a feedstock. Valorisation of ethanol to ethylene is limited in EU. More R&D needed to reduce costs	Need for stable and cost-effective waste streams supply chain (-) Competition with electricity and bio-fuels (-)	n.a	Wyns and Axelson
Production of polylactic acid (PLA) from bio-based materials	PLA production from sugar beet pulp or corn starch	n.a.	Pilot plant in Belgium On industrial scale outside of Europe	Stable and cost-effective waste streams supply chain needed (-) Competition with electricity and bio-fuels (-)	n.a	Wyns and Axelson
Alternative Fuels						
Biomass as fuel	Biomass instead of fossil fuels used directly in combustion or converted into syngas via gasification or methane with anaerobic digestion	85% CO_2 emission reduction	Direct combustion is commercially available, gasification is at pilot stage	n.a	Total cost for the UK sector: £ 1,000,000,000	DECC

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
Waste as fuel	Using waste-derived fuel	100% CO_2 emission reduction	Commercially available	n.a	Total cost for the UK sector: £ 500,000,000	DECC
Decarbonised methane as a fuel	Replacing natural gas with methane from anaerobic digestion or hydrogen generated by renewable sources	100% CO_2 emission reduction	Anaerobic digestion is commercially available; hydrogen is at pilot stage	n.a	Total cost for the UK sector: £ 4,500,000,000	DECC, UBA

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
Recycling/ Valorisation of Waste						
Valorisation of waste mechanical recycling (back to polymer)	Collection and mechanical processing of waste plastics to produce recycled polymers	Mechanical recycling for streams that are easy to collect and clean are 25 - 60% less energy-intensive than production of primary polymers	Post-consumer waste entering mechanical recycling operations increased from 16% to 25% of the waste collected between 2006 and 2010	High cost (-) Type of waste collection schemes differs regionally (-) Quality of waste streams and availability vary Quality of primary polymer may be superior to recycled polymer (-)	Cost of recycling: Between 100 and 1200 €/t depending on the type of plastic, location, collection scheme and type of processing	CEFIC
Valorisation of waste Feedstock recycling (back to monomer)	Breaking down certain polymers into their monomers via chemical process	n.a	Glycolysis, methanolysis and alkaline hydrolysis – commercially available	The product can directly replace virgin monomers (+) More expensive than mechanical recycling (-) Production cost exceeds market price of the virgin monomer (-)	n.a	CEFIC
Heat recovery						
Heat recovery and reuse - on-site process integration (pinch analysis)	Improving effectiveness of heat use on a chemical site by matching supply and demand of heat as much as possible including energy storage	Fuel savings of 5% can be achieved Concentration of chemical activities in mega-clusters (“chemical parks”) can increase the potential	n.a	n.a	n.a	CEFIC, UBA

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
Heat recovery and reuse – upgrade quality of waste heat / electricity generation	All novel processes where heat that is currently not utilized can be transferred to a medium (heat pumps with high temperature lifts, thermally driven cold supply etc.) and turned into power via the Organic Rankine Cycle (ORC)	n.a	Commercially available	The maximum temperature lift that can be achieved is limited (-) Cost for ORC is higher than other power generation technologies (-)	n.a	CEFIC, UBA
Heat recovery and reuse – district heating	Using waste heat from chemical site for district heating or in the production process, e.g. pre-heating input with low grade heat from used cooling streams	(DECC) 2% CO_2 emission reduction	n.a	Economic viability depends on distribution network and integration between facilities (-) Risk in security of supply (-) Limiting factor for further improvements reducing waste heat (-)	(DECC) Total cost for the UK sector: £ 140,000,000n.	CEFIC, DECC
Energy Efficiency						
Efficient usage of motor systems	Use of properly sized and energy efficient motors Use of variable-speed drives (VSDs) Optimisation of the complete system	17– 30% electricity savings	n.a	n.a	n.a	CEFIC, UBA
Improved process control	Improvements in control and operation of	1% CO_2 emission reduction	Commercially available	n.a	Total cost for the UK sector: £ 34,000,000	DECC, UBA

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
	processes and unit operations to reduce energy consumption					
Efficient equipment	Deployment of more efficient equipment such as motor drives, compressors, chillers	4% CO_2 emission reduction	Commercially available	n.a	Total cost for the UK sector: £ 440,000,000	DECC, UBA
Process intensification (PI)	Innovations in equipment (novel reactors and furnaces, intensive mixing, heat-transfer and mass-transfer devices) and process design (integration of reaction and separation, heat exchange, phase transition, techniques using alternative energy sources, and new process-control methods to improve efficiency)	n.a	n.a	High costs to retrofit process intensification technologies (-) Lack of knowledge (-) Long development path (-)	n.a	CEFIC, UBA
Energy efficiency improvements to on-site energy	More efficient boilers (improved process control, offline or online supply-demand optimisation using MILP (mixed integer linear	(CEFIC) Up to 10% fuel savings (DECC) 4% CO_2 emission reduction	High level of implementation in Europe	- Limited potential for Europe (-)	(DECC) Total cost of steam efficiency improvements in UK sector; £ 44,000,000n.a	CEFIC, DECC, UBA

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
generation and distribution	programming), reduced flue gas quantity, flue gas heat recovery, and regular maintenance), fuel savings in steam distribution systems (improved and better maintained steam traps, leakage repair and condensate return), better insulation					
Combined generation of heat and power (CHP)	Producing electricity and useful heat from one system that can also be used in biomass applications.	(DECC) 8% CO_2 emission reduction.	High level of implementation in Europe	Current low natural gas and electricity prices (-) With the improvements in renewables, fossil-fuelled CHP might have higher energy intensity than centralized power production (-)	n.a	CEFIC, DECC
N_2O abatement options in nitric acid production	Integrated abatement measures to remove N_2O from process gas steam End-of-pipe abatement measures to reduce N_2O after the absorption process	From current 0.9 kg N_2O / t nitric acid to 0.7 kg N_2O/t nitric acid (2020) and 0.3 kg N_2O/t nitric acid (2050) With new nitric acid plants 0.1 kg N_2O/t nitric acid	n.a	n.a	7 to 190 €/t CO_2eq. depending on the type of measure, the current layout of the plant and temperatures of the tail gas	CEFIC, UBA
Energy consumption	Current measures: adding pre-reformer,	From 35 GJ / t NH_3 to 32 GJ / t NH_3	Current measures are mostly	Limited effect on European industry (-)	n.a	CEFIC

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
reduction measures in ammonia production	insulation, lowering steam-to-carbon ratio, increase operating pressure Additional measures: improved CO_2-removal, low-pressure ammonia synthesis by using improved catalysts, advanced integration of the heat exchanger network in the plant, improved process control and improved motor systems, heat recovery systems		implemented in the European chemical industry			
Improved insulation	Improve insulation to reduce heat losses	1% CO_2 emission reduction	Commercially available		Total cost for the UK sector: £ 84,000,000	DECC
High temperature cracking	Usage of high temp. furnaces in cracking process	2% CO_2 emission reduction	Verified technology, but not commercial	n.a	n.a	DECC
Clustering	Connecting the industrial sites by locating them close to each other to improve efficiency	25% CO_2 emission reduction	Commercially available	n.a	n.a	DECC
Methanol to olefins	Production of olefins from natural gas via	10% CO_2 emission reduction	Available technology but not	n.a	n.a	DECC

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
	methanol to replace steam cracking of naphtha or ethane		yet on commercial scale			

4.4.3.2 Innovative technologies

Table 52: Innovative technologies – Chemical industry

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
Valorisation of waste Feedstock recycling back to feedstock	Breaking down polymers into hydrocarbons or a mixture of carbon monoxide and hydrogen via thermal process	(DECC) 8% CO_2 emission reduction	Torrefaction, pyrolysis and gasification – R&D	Limited competition in comparison with steam cracking to produce cracker products (-)	n.a	CEFIC, DECC
Production of furandicarboxylic acid (FDCA)	FDCA is a key component in the production of bio-based polyethylene furanoate (PEF), which can replace polyethylene terephthalate (PET)	n.a.	R&D phase	Improved mechanical strength compared to PET enables thinner packaging plastic (+)	n.a	Wyns and Axelson

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
Carbon capture and utilisation (CCU)	Usage of captured CO_2 in the fabrication or synthesis of products. Other applications: enhance hydrocarbon production, greenhouses, soft drinks, fuel production, raw material for inorganics	(DECC) 77% CO_2 emission reduction	Polymers and fine chemicals synthesised from CO_2 – available but not commercial	High energy demand to convert CO_2 into value added products (-) Purification and further treatment is needed in order to use the captured CO_2 for applications in the chemical industry (-)	n.a	CEFIC, DECC
Geothermal heat usage	Using geothermal energy to cover some of the heat demand	n.a	Might be feasible in the future	Geographical availability (-) Heat sources from cascading has priority usage (-) Difficult to find financing for the upfront investments (-)	5.4 € / GJ in 2050	CEFIC
Carbon capture and storage general (CCS)	Post-combustion (capture from flue gases), pre-combustion (capture by conversion of fuels) or oxy-fuel (capture by combustion with pure oxygen instead of air)	(DECC) 80% CO_2 emission reduction	Available but not commercialized	n.a	From combustion sources* In 2020 with 85% capture rate: Between 1160 €/t CO_2 captured and 340 €/t CO_2 In 2050 with 95% capture rate: Between 742 €/t CO_2 captured and 255 €/t CO_2 From process emissions;	CEFIC, DECC

Technology	**Short description**	**CO_2 saving potential**	**Status**	**Advantages (+) / restrictions (-), according to the respective study**	**Cost of the technology**	**Included in the studies**
					In 2020 with 100% capture rate: Between 240 €/t CO_2 captured and 170 €/t CO_2 In 2050 with 100% capture rate: Between 210 €/t CO_2 captured and 172 €/t CO_2	
CCS -ammonia or hydrogenproduction	Deployment of CCS on process emissions from the steam methane reforming process to make ammonia or hydrogen	90% CO_2 emission reduction	Pilot	n.a	Total cost for UK sector: for ammonia £ 100,000,000 for hydrogen £ 33,000,000	DECC
Solid State Ammonia Synthesis (SSAS)	Hydrogen production by electrolysis of water or by using a combination of electrolysis and Haber-Bosch synthesis loop (SSAS)	(CEFIC, DECC) Both electrolysis and SSAS processes only depend on electricity. With the decarbonisation of power sector, the emissions will be zero	Hydrogen production by electrolysis of water viable after 2030 1st. SASS plant is being built in USA	Both technology emissions depend on energy mix (Wyns and Axelson) SASS Higher efficiency (+) Lower cost (+) Can be a storage for hydrogen (+)	n.a	CEFIC, Wyns and Axelson, UBA, DECC
High temperature steam electrolysis	Nuclear high temperature steam electrolysis	Zero emissions	R&D	n.a	n.a	Wyns and Axelson, DECC

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
Improvements in energy efficiency in existing cracker product** plants	Process and heat recovery improvements in furnace section, fractionation and compression section and recovery and separation section	23-34% energy efficiency improvements in 2050 compared to 2010	Early membrane separation of alkanes – R&D No information given about other improvement options	Viability depends on current integration of sites	n.a	CEFIC
Integrated gas turbines with cracking furnace	Integrating turbines with cracking heaters to produce electricity or drive compressors	10% CO_2 emission reduction	Pilot	n.a	n.a	DECC
New plants for cracker product production	Catalytic cracking of naphtha instead of steam cracking. Alternative processes to produce specific types of olefins like ethylene or propylene mostly from biomass	Reduction from 11 – 14 GJ /tonne cracker products to 9 GJ / tonne cracker	n.a	n.a	n.a	CEFIC
Energy saving options in chlorine production	Converting mercury cells to membrane cells Changing monopolar to bipolar membrane Retrofitting membrane cell plants operating in	(CEFIC) From 10 GJ / tonne CL_2 to 6.6 GJ /tonne (DECC) 23% CO_2 emission reduction	(DECC) Pilot	n.a	Investment cost for membrane cell conversion; € 500 per tonne of annual chlorine capacity (40 – 50% of a new membrane plant) Investment cost for ODC; € 70-100 per tonne	CEFIC, DECC

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
	2010 to oxygen-depolarised cathodes (ODC)				of annual chlorine capacity	
Use of bio-based waste (the NEWFERT project)	New production process for fertilizer from bio-based waste to replace commercial fertilizer based on nitrogen and phosphorus	n.a	n.a	n.a	n.a	Wyns and Axelson
N-Fix	Using the bacteria gluconacetobacter diazotrophicus (Gd) for coating plant seeds to obtain nitrogen from atmosphere	50% savings of ammonia-fertilizer usage	n.a	n.a	n.a	Wyns and Axelson
Membrane technology	Replace high energy-intensive processes like distillation with membrane technologies	8% CO_2 emission reduction	R&D	n.a	n.a	DECC
Process intensification	Implementation of process intensification techniques like miniaturisation,	8% CO_2 emission reduction	R&D	n.a	n.a	DECC

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
	synergies between process steps					
Catalytic cracking	Replace current steam cracking with catalytic cracking	15% CO_2 emission reduction	Pilot	n.a	n.a	DECC

4.4.4 Cement Industry

4.4.4.1 Currently available technologies

Table 53: Currently available technologies – Cement industry

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
Alternative materials and fuel						

Technology	**Short description**	**CO_2 saving potential**	**Status**	**Advantages (+) / restrictions (-), according to the respective study**	**Cost of the technology**	**Included in the studies**
Alternative fuel usage	Replacement of coal and pet coke by alternative fossil fuels and biomass to heat the cement kilns. Alternative fuels can be: domestic waste, discarded tyres, sludge, waste oil and solvents, plastic, textile and paper residues, biomass	(CEMBUREAU) 60% of kiln energy potentially come from alternative fuels (technically 80% and more alternative fuels would be possible) leading to 27% decrease in CO_2 emissions from fuel usage compared to 1990 (IEA) 18% reduction in emissions in 2050 compared to 2006 (DECC) natural gas as fuel leads to 7% CO_2 emission reduction to 2012 (25% practical applicability, biomass to 31% to 2012 (80% practical applicability)	(CEMBUREAU) 8.7% biomass use as fuel in EU in 2011 26% fossil waste as fuel in 2011 and 80% of the cement plants make use of waste (DECC) 18% biomass as fuel adopted by UK, natural gas is under R&D	Increased access is needed to secure, continuous and affordable waste and biomass (-) Physical and chemical properties of alternative fuel (-) Pre-treatment might be needed for more uniform composition (-) Waste management legislations (-) Inadequate waste collection (-) Social acceptance (-)	(DECC) Fuel switch to natural gas capex: £7,500,000 per site Fuel switching to biomass capex: £7,500,000 per site	CEMBUREAU, IEA, CS C, DECC

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
Raw material substitution	Partial substitution of limestone by waste and industrial by-products that contain calcium, silica, alumina and iron. Waste products: sewage sludge, waste concrete from constructions as limestone substitute, ashes from lignite, coal, BF slag, concrete crusher sand, aerated concrete meal as alternative for virgin limestone	(DECC) 67% CO_2 emission reduction	(CEMBUREAU) In recent years 3-4% of raw materials for clinker production in Europe (~14.5 Mt/year) consisted of alternative raw materials and ashes from fuel,	Dependence on materials close to the cement plant. Restrictions may arise if the materials consist of silica, alumina, magnesium, sulphur or VOCs (-) Limited availability of decarbonized material close to the cement plant (-) Operating and storage costs for handling alternative material (-) Improved energy efficiency (+)	(DECC) No cost for the main process.	CEMBUREAU, DECC

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
Clinker substitution	Blending clinker with alternative materials to reduce clinker-to-cement ratio. These materials can be: natural pozzolans like shale, clay and certain types of sedimentary rock, finely ground limestone, silica fume (a by-product of silicon production), granulated blast furnace slag (GBFS) (a by-product of iron-steel production), fly ash, flue gas from coal-powered power stations and burnt oil shale	(CEMBUREAU) Reduction of clinker-to-cement ratio to 70% results in 4% CO_2 emission reduction Some studies assume that even further reduction of the clinker share is possible down to 65% (van Ruijven et al. 2016).) or even 52 to 61% (BMUB 2015)	(CEMBUREAU) Global clinker-to-cement ratio in 2006 is 78% Current clinker-to-cement ratio in EU is 73.7%	Local supply of materials (-) The alternative material quality compared to clinker-based cement (-) Availability of the material close to the plant (-) Limiting factor for future production of by-products e.g. fly ash from coal-powered power plants(-)	n.a	CEMBUREAU, IEA, CS C, UBA, BMUB

Technology	**Short description**	**CO_2 saving potential**	**Status**	**Advantages (+) / restrictions (-), according to the respective study**	**Cost of the technology**	**Included in the studies**
Efficiency measures						
Electrical energy efficiency (indirect emissions)	Replacement of older plants, modernising existing plants, advancement of grinding techniques, using modern clinker cooling technologies, and variable speed drives, voltage and power optimisation, strategic motor selection and optimisation, high energy efficiency belts	(CEMBUREAU) No impact on reducing direct emissions (DECC) 5% electricity consumption reduction	Commercially available (DECC) Not realized in UK plants	n.a	(DECC) Capex: £30,000,000 per site	CEMBUREAU, DECC, UBA
Thermal energy efficiency	Waste Heat Recovery (WHR) systems, replacing old wet kilns by modern plants and preheater kilns with precalciners (PH-PC). (PH-PC consumes 85% less energy than old wet kilns)	11.5% energy reduction 2050 to 2010 (from 3.73 MJ/t clinker in 2010 to 3.3 MJ/t clinker in 2050)	Retrofitting old plants with new technology → Most EU plants are using state-of-the-art technologies in terms of thermal energy optimisation WHR – commonly used in China	High initial investment of WHR (-) Increase in power consumption (-)	n.a	CEMBUREAU, van Ruijven et al. 2016, UBA

Technology	**Short description**	**CO_2 saving potential**	**Status**	**Advantages (+) / restrictions (-), according to the respective study**	**Cost of the technology**	**Included in the studies**
Dry manufacturing process with preheater and precalciner (PHPC)	The current state of the art technology in clinker production	(IEA) Lower energy consumption than wet clinker process by 3 GJ/t clinker (CSC) 50% energy savings compared to wet clinker production	Applied to newly built plants 44% in EU in 2011	Needs high investment (-) May increase power demand (-) Cost of carbon (between €10-20) is not high enough to give the incentive to replace the wet kiln by a dry kiln (-)	n.a	IEA, CS C, van Ruijven et al., UBA
Electricity from waste heat	Using waste heat for drying and power generation by organic ranking cycle or Kalina cycle	1% reduction in electricity consumption	System is complete and qualified but not commercially available	n.a	Capex: £11,000,000	DECC, UBA
Kiln process technology (BAT kiln)	Modernizing the kilns with the best available technologies	1% CO_2 emission reduction	Not applied yet	n.a	Capex: £180,000,000 per site	DECC, UBA

4.4.4.2 Innovative Technologies

Table 54: Innovative technologies – Cement industry

Technology	**Short description**	**CO_2 saving potential**	**Status**	**Advantages (+) / restrictions (-), according to the respective study**	**Cost of the technology**	**Included in the studies**
Novel cements	Different materials: magnesium silicate rather than limestone, calcium sulfo-aluminate belite	(CEMBUREAU) 5% share of novel cement is	(CEMBUREAU) R&D and small-scale production	(CEMBUREAU) Good for niche activities (+) Availability in large quantities (-)	(DECC) capex: £220,000 per site	CEMBUREAU, UBA, DECC

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
	binders, calcium and magnesium hydroxides, geopolymer cement New production techniques: using an autoclave instead of a kiln, special activation grinding technique, which requires less heat, rapid calcination of dolomite rock in superheated steam	foreseen/ (UBA) 50% in climate-neutral Germany (DECC) 50% CO_2 emission reduction	(DECC) commercially available but not realized in UK	Need more tests to produce larger volumes (-) (DECC) Practical applicability is only 5% (-)		
CCS						
Carbon capture via post-combustion	Post-combustion; end-of-pipe mechanisms such as chemical absorption, membrane technologies, carbonate looping (production of calcium carbonate from the contact of calcium oxide with CO_2)	To reach 80% reduction and without any other breakthrough technologies, carbon capture should be applied to 85% of all clinker production plants	(CEMBUREAU) Post-combustion; currently tested in other industries (like power) but still under R&D in cement	High capital and operating costs (-) Not competitive with non-carbon capture deployed plants (-) Lack of knowledge to make it competitive (-) European, national, regional and local support is needed (-) Does not require fundamental changes to the existing facilities (+) Requires pure CO_2, thus NO_2, SO_2 and dust removal is needed (-)	(CEMBUREAU) €100-300 million per plant to retrofit existing plant with post-combustion technology 25% increase in operating cost with oxyfuel	CEMBUREAU, CS C, van Ruijven et al., Wyns and Axelson, BMUB
Carbon capture via oxyfuel combustion	Oxyfuel combustion; using oxygen instead of air in the kilns to obtain pure CO_2	90% CO_2 emission reduction	(CEMBUREAU) R&D (DECC) Demonstration	Additional energy is needed to produce oxygen (-) Can lead to higher wear and tear in the kiln due to the higher temperatures reached with oxygenation (-) High capital and operating costs (-) Not competitive with non-carbon capture deployed plants (-)	(CEMBUREAU) €330-360 million per plant for oxyfuel at a new 1 Mt/ year plant, €100 million per plant for retrofitting with oxyfuel	CEMBUREAU, CS C, van Ruijven et al., Wyns and Axelson, DECC, BMUB

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
				Lack of knowledge to make it competitive (-) European, national, regional and local support is needed (-)	(DECC) capex: £100,000,000 per site	
Biological carbon capture	Using algae to capture CO_2. After the carbon absorption, it can be used as a fuel.	n.a	R&D	n.a	n.a	CEMBUREAU
CCS through calcium looping cycle	Using solid CaO (lime)- based sorbets to obtain concentrated CO_2 (95%) from flue gas	potential 80% CO_2 capture	Pilot in Taiwan	Final product is suitable for storage (+) Low cost due to the cheap sorbent (+) Most promising economically viable CCS option (+)	40 USD / ton CO_2 captured	Wyns and Axelson
Innovative clinker substitution						
Other options for clinker substitution – Kaolin clay	Using Kaolin clays as a substitute	n.a	No current application	Kaolin clays need thermal treatment before usage (-)	n.a	Wyns and Axelson
Other options for clinker substitution – Magnesite	Using magnesite as a substitute	n.a	n.a	Available only in small amounts in EU, not enough to be used in Portland cement	n.a	Wyns and Axelson
Other options for	A geo-polymer resulting from gas-plasma technology to turn part of	3 to 11 Mt annual CO_2 reduction in	n.a	n.a	n.a	Wyns and Axelson

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
clinker substitution – Plasmarok	recovered waste into syngas in enhanced landfill mining (ELFM)	EU (3 to 11% of current emissions)				
Other options for clinker substitution – Belite, Ye'elimite and Ferrite	Using Belite, Ye'elimite and Ferrite as a substitute under the name of Aether®	30% lower emissions compared to traditional clinker	R&D	100-200 °C lower temperatures needed than in traditional clinker production (+) Portland cement quality can be achieved Most promising option for substitutions in future	n.a	Wyns and Axelson
Process Innovations						
Limestone reduction through electrolysis	The CO_2 produced in the transition from limestone to lime is further reduced in the electrolysis process inside molten carbonate resulting in CO or pure carbon	n.a	R&D No plans to apply on a larger scale	Can be economically viable on a larger scale through valorization of CO as feedstock in chemical processes (+)	n.a	Wyns and Axelson
Fluidised bed kiln	Clinker production in a fluidised bed kiln under the addition of ground coal and raw material injection. Clinker is cooled by fluidised bed quenching and a packed bed cooler	3% CO_2 emission reduction	R&D	n.a	n.a	DECC
Oxygen enrichment technology	Using oxygen enriched combustion air in the clinker burning process	3% CO_2 emission reduction	Pilot	n.a	Capex: £6,000,000 per site	DECC

4.4.5 Ceramics Industry

4.4.5.1 Currently available technologies

Table 55: Currently available technologies – Ceramics industry

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
Improved thermal efficiency of materials	Improved kilns, dryers, thermostats and seals Automated controls Improved thermal insulation via novel refractory linings, coatings and other ceramic materials, large tunnel kilns	(DECC) 15% CO_2 emission reduction	Applied in the EU	n.a	n.a	Ceramie-Unie, DECC
On-site renewable energy production and CHP	Energy production from renewable energy facilities or on-site CHP plant	n.a	On-site renewable energy plants – applied in the EU CHP - commonly used in the EU	Installation of renewable energy plants encounters legal difficulties (-)	Capex per site for CHP for the dryer: £2,000,000	Ceramie-Unie, DECC
Use of local raw material	Locally provided raw materials reduce the emissions from long-distance transportation	n.a	n.a	Not feasible to relocate current facilities, only feasible for new facilities	n.a	
Organic Rankine Cycle (ORC) for heat recovery	Heat recovery by ORC	Electricity savings	Commercially available but not applied in UK	n.a	Capex per site; £250,000	DECC

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
Improved insulation and maintenance		7.5% CO_2 emission reduction	Commercially available 36% adopted in UK	n.a	Capex per site; £5,000,000	DECC
Adoption of BAT kilns	Best available technologies in ceramic kilns	11% - 30% CO_2 emission reduction depending on the subsector	Commercially available 6% - 15% adopted in different kilns in UK	n.a	Capex per site; £1,000,000 - 20,000,000 depending on the subsector	DECC
Apply Variable Speed Drive (VSD) to variable duty pumps/ fans	Replacement of throttling via VSD	Minimum reduction in electricity use	Commercially available 10% adopted in UK	n.a	Capex per site; £100,000	DECC
Improve combustion efficiency	Maintaining a constant air/fuel ratio over the range of burner outputs	4% CO_2 emission reduction	Commercially available 68% adopted in UK	Enhance fuel efficiency (+)	Capex per site; £200,000	DECC
Improved process control	Better monitoring and control of firing process	2% CO_2 emission reduction	Commercially available 65% adopted in UK	Better uniformity of output (+) Reduced fuel consumption (+)	Capex per site; £250,000	DECC
Reduction of product mass in bricks or in white ware	Reducing the product mass	5% CO_2 emission reduction in heavy clays 10% in white ware	Commercially available 22% adopted in heavy clays, not yet adopted in white ware in UK	Reduces specific energy consumption	Capex per site; 0-£500,000 depending on the subsector	DECC

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
Low mass refractory for kiln cars	Reduction of heat load by low mass refractory	5% - 20% CO_2 emission reduction	Commercially available 20% - 27% adopted in different kilns in UK	n.a	Capex per site; £1,000,000 - 1,750,000 depending on the subsector	DECC
Pre-calcining of clay in heavy clays sector	Pre-calcining of 80% of the clay in a fluidised bed	5% CO_2 emission reduction	Commercially available 2% adopted in UK	n.a	Capex per site; £5,000,000	DECC
Preheat water added for forming heavy clays	Using hot water for forming instead of cold	3% CO_2 emission reduction	Commercially available Not yet adopted in UK	Reduce drying requirements	Capex per site; £100,000	DECC
Reduce air/product mass ratio in heavy clays	Maximizing the kiln loading by reducing air	10% CO_2 emission reduction	Commercially available 20% adopted in UK	Reduce energy requirement per ton of product	Capex per site; £100,000	DECC
Oxy-fuel firing/ oxygen enrichment in refractories	Extreme temperature firings to reduce exhaust gas resulting from oxygen enriched or oxy-fuel combustion	13% CO_2 emission reduction	Commercially available 7% adopted in UK		Capex per site; £100,000	DECC
Pulse firing of kilns in refractories	Pulse firing rather than continuous firing reduces the gas flow through the kiln	6.5% CO_2 emission reduction	Commercially available 10% adopted in UK	Reduces heat losses	Capex per site; £100,000	DECC

Technology	**Short description**	**CO_2 saving potential**	**Status**	**Advantages (+) / restrictions (-), according to the respective study**	**Cost of the technology**	**Included in the studies**
Re-use heat regeneratively	Preheat combustion air by heat exchange with flue gases	8% - 20% CO_2 emission reduction depending on the subsector	Commercially available 16% - 60% adopted in different kilns in UK	requires suitable heat exchangers (-)	Capex per site; £20,000 - 200,000 depending on the subsector	DECC
Reduce number of firings	Reduction of number of firings	15% - 17% CO_2 emission reduction	Commercially available in technical ceramic sector, pilot in white ware Not yet adopted in UK	n.a	No cost	DECC
Improve waste heat recovery in white ware sector	Recovering heat from flue gases or from cooling ware or from the kiln environment to be used elsewhere	6.5% CO_2 emission reduction if used in the process 2% if used elsewhere	Commercially available Using waste heat from flue gases and cooling ware is not adopted in UK but using waste heat from the kiln environment is 5% adopted	Reduce energy consumption in drying	Capex per site; £100,000	DECC
Increase pack density in white wares	Increasing the pack density	30% CO_2 emission reduction	Commercially available Not yet adopted in UK	Better utilization of the kiln Reduction in specific energy consumption	No cost	DECC

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
Optimise kiln circulation in white wares	Improving the management of air flows in kilns	30% CO_2 emission reduction	Commercially available 5% adopted in UK	Reduce heat losses	Capex per site; £100,000	DECC
Temperature reduction in white wares	Optimisation of body and glaze materials to reduce the firing temperature	5% CO_2 emission reduction	Commercially available 21% adopted in UK	n.a	No cost	DECC

4.4.5.2 Innovative technologies

Table 56: Innovative technologies – Ceramics industry

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
Electrification of kilns	New kiln design using low-carbon electricity	(DECC) 80% CO_2 emission reduction with low-carbon electricity	No application in the EU	Economically not feasible due to high electricity prices (-)	(DECC) Capex per site; £20,000,000	Ceramie-Unie, DECC
Recovery of heat	Capturing kiln gases in order to preheat combustion or dryer air	n.a	n.a	n.a	n.a	Ceramie-Unie
On-site renewable energy production – solar ovens	Oven fired with solar power for drying processes	n.a	R&D	Installation of renewable energy plants encounter legal difficulties (-)	n.a	Ceramie-Unie

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
Syngas or biogas production from biowaste	Replacement of natural gas by syngas or bio-gas. Substitution rate of 80% is technically possible	30% reduction in CO_2 emissions	R&D	Bio-gas is three times more expensive than natural gas (-) European public-private partnership of the process industries (SPIRE) said to be important for development of the technology Long-term waste or bio-mass supply is needed (-)	(DECC) Capex per site; £15,000,000	Ceramie-Unie, DECC
Adding biomass to heavy clays	Addition of finely divided biomass to clay	5% CO_2 emission reduction	n.a	Reduces the need for fuel during firing (+)	No cost	DECC
Carbon Capture and Storage	Application of CCS to ceramic production facilities that are widespread and smaller in size	(DECC) 50% CO_2 emission reduction in heavy clays if applied	(Ceramie-Unie) No application for ceramic industry (DECC) Demonstration	With current technology, not feasible to apply at ceramic facilities. Breakthrough technology needed to scale it to ceramic industry (-) Likely to be applied after commercialization in larger industries	Capex per heavy clay site; £10,000,000	Ceramie-Unie
Using low carbonate clay for yellow bricks in heavy clay subsector	Production of yellow bricks with low carbonate clay options with colorant instead of conventional clay	10% CO_2 emission reduction	Verified technology, but not yet commercial	n.a	No cost	DECC

Technology	**Short description**	**CO_2 saving potential**	**Status**	**Advantages (+) / restrictions (-), according to the respective study**	**Cost of the technology**	**Included in the studies**
Low mass insulation and refractories	Refractories for extreme temperatures	20% - 50% CO_2 emission reduction depending on subsector	Pilot	n.a	Capex per site; £200,000	DECC

4.4.6 Lime Industry

4.4.6.1 Currently available technologies

Table 57: Currently available technologies – Lime industry

Technology	**Short Description**	**CO_2 Saving Potential**	**Status**	**Advantages (+) / restrictions (-), according to the respective study**	**Cost of the technology**	**Included in the studies**
Parallel flow regenerative lime kilns (PFRK)	Most energy efficient vertical kiln	n.a	80% of kilns in the EU are vertical kilns, 39% of kilns are PFRK	Small particles like chalk limestone cannot be processed, thus not suitable for all types of lime production (-)	n.a	Ecofys
Rotary kiln with pre- heater (PRK)	Usage of heat exchangers in horizontal kilns to recover heat from flue gas	Switching all LRK to PRK could achieve a 30% reduction in combustion-related emissions from existing LRKs	More than half of horizontal kilns that account for 20% of all kilns are PRKs	n.a	Abatement cost: 38 €/t CO_2 Investment cost: 72.5 €/t per year	Ecofys
Improved use of heat Energy recovery from hydration	Effective use of waste heat for drying, milling in the sector and processes	n.a	Some examples in the EU	Contractual obligations (-) Cost of delivering waste heat (-)	n.a	Ecofys

Technology	Short Description	CO_2 Saving Potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
	in other sectors or buildings and residential areas. Converting heat into electricity using the Organic Rankine Cycle (ORC)			Availability of other industries close to the lime plant (-) For ORC: installation cost (-)		
Fuel switch from solid fossil fuel to gas	Using natural gas as a fuel instead of fossil solid fuels	28% reduction in combustion emissions	Current share of natural gas is 34%, fossil solid fuel accounts for 51%	High cost of natural gas (-) Security of gas supply(-) Some products cannot be produced using gas due to technical and economical limitations (-) Connection to the natural gas grid (-)	Abatement cost: 91 €/t CO_2 Investment cost: none	Ecofys
Waste as fuel	Using different forms of waste as fuel	n.a	Current share of waste in fuel mix is 8%	Quality of waste fuel (-) Not all kilns can process all types of waste (-) Legislations in different member states might play a role (-)	n.a	Ecofys
Solid biomass as fuel - wood	Using solid biomass as fuel	Switching all fuel to biomass will eradicate energy related emissions	Currently used in the EU Other types of solid biomass (olive stones; coconut cores, sugar cane, jatropha nuts and rice hull) – undergoing R&D	Interaction with material might create problems in certain types of production processes (-) Biomass may cause kiln blockage (-) High maintenance cost (-)	n.a	Ecofys

4.4.6.2 Innovative technologies

Table 58: Innovative technologies – Lime industry

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
Solid biomass as fuel – other types of biomass (olive stones; coconut cores, sugar cane, jatropha nuts and rice hull)	Using solid biomass as fuel	Switching all fuel to biomass will eradicate emissions	R&D	Interaction with material might create problems in certain type of production processes (-) Biomass may cause kiln blockage (-) High maintenance cost (-)	n.a	Ecofys
Gaseous biomass as fuel	Using syngas from biomass as fuel	n.a	R&D	n.a	n.a	Ecofys
Using electricity to heat kilns	Production of lime from electricity	n.a	Requires R&D	Not yet economically attractive (-)	n.a	Ecofys
Heat production for kilns by high temperature Solar Central Receiver Systems (CRS) with pressurised air	Using CRS to produce heat up to 1000 °C in kilns	n.a	R&D	n.a	n.a	Ecofys
CCS / CCU	Carbon Capture and Storage/utilization	70% of all emissions	n.a	n.a	Abatement cost: 94 €/t CO_2 Investment cost: 76 €/t CO_2 avoided	Ecofys

4.4.7 Aluminium Industry

4.4.7.1 Currently available technologies

Table 59: Currently available technologies – Aluminium industry

Technology	Short description	CO_2 saving potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
Recycling	Using scrap aluminium instead of primary production	95% energy saving compared to primary production	n.a	Leakage of aluminium scrap to other countries (-)	n.a	EAA

4.4.7.2 Innovative technologies

Table 60: Innovative technologies – Aluminium industry

Technology	Short Description	CO_2 Saving Potential	Status	Advantages (+) / restrictions (-), according to the respective study	Cost of the technology	Included in the studies
New technologies to replace carbon anode consumption, e.g. inert anodes	Substitution of carbon anode consumption, which is currently the only technology for smelting/ electrolysis	n.a	R&D, expected to be commercialized in 2030	n.a	n.a	EAA, UBA

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