Technological developments in Europe

A long-term view of CO_2 efficient manufacturing in the European region

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Author(s):
Harry Croezen
Marisa Korteland

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Harry Croezen, Marisa Korteland
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CE Delfts solutions are characterised in being politically feasible, technologically sound, economically prudent and socially equitable.

Preface

In this report we adopt a long-term perspective of technological innovations regarding CO_2 efficiency. We have painted a picture of promising technological options, based on our expertise, conversations with stakeholders and as much publicly available information as possible.

We would like to express our gratitude to the following persons that have provided information and shared their vision with us:
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CE Delft remains, of course, responsible for final content of this report.

Of course, it is always difficult to look at future developments. No one has a monopoly on wisdom there. Since this report reflects current knowledge on future developments, it inherently contains uncertainties.

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Executive summary

Introduction

For years political debates have been centred on finding a balance between fostering economic growth, meaning increased production activities, and avoiding permanent damage to the environment caused by such activities. With respect to climate change, the EU has formulated its ambition to limit the global average temperature rise to 2 degrees Celsius above pre-industrial level in order to reduce the risk of climate change. In line with this goal, the EU has set a target to reduce domestic greenhouse gas emissions by at least 20% in 2020 and aims to cut in emissions by 80-95% in 2050, all relative to a 1990 baseline. Significant CO_2 reductions will be needed. Since it is neither a realistic nor an attractive option to avoid investments in production capacity and abandon all energy-intensive industries from Europe, increasing the efficiency of the industrial process is crucial. Innovation plays an important role here[1]. This study identifies technologies in a number of industrial sectors that may well have the potential to bring about a gradual change in CO_2 emissions. The main aim of this explorative study is to identify whether the innovations under development yield the possibility of realising the required reduction in CO_2 emissions of 80-95% (compared to current emission levels) in the respective industrial sectors. Opportunities and potential technical, economic and social bottlenecks for large-scale implementation are also mentioned.

Main conclusions

This study indicates that significant emission reductions seem possible in the steel, paper and cement manufacturing, together accounting for 41% of the European industrial CO_2 emissions. Based on the available information, several promising technologies with repect to CO_2 efficiency have been identified in these sectors. They seem to have the potential to produce significantly lower CO_2 emissions per unit of product compared to the current average production plant in Europe. Since these technologies are currently in pilot stages of technological development and are expected to become commercially available between 2020 and 2030, a significant reduction in CO_2 emissions until 2050 seems viable. The identified technologies are described in more detail in the next paragraph of this summary.

Broadly speaking, the identified technologies have been classified into three categories:

1. Breakthrough technologies

   In the context of this study, technologies are defined as breakthrough when:

   - They yield CO_2 emission reductions of 25% or more compared with current average technology.
   - Become commercially available in 2020–2030[2] and have the potential for wide implementation in the sector in the period up to 2050.
   - Can be expected to be economically competitive compared to the current and future reference technologies.

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[1] In the light of rising (oil and) energy prices, technical development is not only crucial from an environmental but also from a business perspective.

[2] This means that they are currently at least in or close to the pilot stage of technological development.

2. Back-up technologies
   These are technological options that fit with existing production processes but do not yield the required CO_2 reductions and/or come at higher costs. They might still be needed in case a particular breakthrough technological innovation turns out to be less successful than expected and for reduction of CO_2 emissions of reference technology installations still existing in 2050.
3. Potential breakthrough technologies
   These technological routes might turn out to be longer-term breakthrough technologies (beyond 2030-2050) if additional R&D is stimulated. They are not in the pilot stage yet or are being applied in other sectors than those considered in this study, but seem to have the potential for realisation of the required CO_2 reduction of 80-95%.

With regard to the types of technologies that can be applied we distinguished between:
- Use of energy carriers with a lower carbon intensity in existing technology, e.g. electricity or biomass instead of natural gas or coal.
- Combination of existing technology with capture of produced CO_2 for perpetual deep geological storage.
- Design a new process which is intrinsically more energy efficient and/or carbon-neutral.

The development of breakthrough technologies aimed at yielding intrinsically more energy efficiency and/or carbon-neutrality seems limited to one development in the cement sector; work on magnesium based clinker which can be a substitute for Portland clinker. In the steel sector, the development of an intrinsically carbon-neutral process in the shape of electrolysis is still very much in the embryonic phase and could be considered a potential breakthrough technology. For the paper sector it would be worthwhile to further explore possibilities for intrinsically more energy efficient paper drying processes. Current energy prices in the last decades have not given enough incentives.In the future, CO_2 prices and costs for fuels and electricity could boost incentive to accelerate the development of the two potential breakthrough technologies identified for the steel and paper sectors.

The utilization of low carbon intensity energy carriers such as biomass and natural gas only seems a back-up measure for the cement and steel sectors. In the cement sector, it would have limited impact on total CO_2 emissions as these are dominated by raw materials related process emissions. In the steel sector, the technical possibilities of utilising low carbon intensity energy carriers in blast furnaces is limited. In the paper sector, biomass already is the main fuel for the most energy-intensive processes.

Possibilities for significant CO_2 emission reduction through the implementation of CCS based breakthrough technologies exist in all three sectors, partly in combination with process innovations in cement and steel sector.

The general conclusion of our inventory is that the innovative technologies currently under development have the potential technically for realising very significant reductions in industrial CO_2 emissions. At the moment most of these innovations rely heavily on CCS in order to achieve this.

The dependency of the breakthrough technologies under development on CCS yields two specific uncertainties and possible disadvantages:

- The lack of solid evidence of the viability of long-term storage has raised public concern and hesitation by environmental NGOs about relying on such a technology.
- If CCS is to be applied, attention must be paid to the possibility that there may be limited storage capacity for CO_2 sequestration. If so the question is whether it should be reserved for industrial use instead of application in the energy sector (coal), where more CO_2 abatement options seem to be available.

More detailed overview and review of considered processes

Table 1 summarises the main characteristics of the identified breakthrough technologies (marked by *) per sector. Most of them are currently available in pilot plants and are expected to be introduced in the market in the medium-term (2020-2030). In addition, Table 1shows potential breakthrough technologies (marked by ^) and back-up options that are more certain or available earlier.

Steel Sector

For the steel sector, coke free steelmaking appears to be the most promising in the medium-term (2020-2030). It is known as the HIsarna technology further explored at Corus (NL) via EU's Ultra Low CO_2 steelmaking (ULCOS) programme.The main features of the technology are that coke is no longer input for the steel process[3] and CO_2 is captured and stored (CCS). An 80% reduction can be reached compared to an average blast furnace. In addition, investment and operational costs lie below average, the latter due to a wider range of (cheaper) inputs that can be used.

The fastmelt process is a valuable short-term option. It is a rotary hearth direct iron-ore reduction process which is already commercially available and yields a reduction of CO_2 emissions compared to the average blast furnace in Europe. Although initial investment costs are relatively high, one main advantage of the technique is that a broader range of inputs can be used for steelmaking, thereby lowering the operational costs.

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[3] Through the use of an entrained bed iron-ore reduction process with integrated smelting bath.

Table 1 **Identified breakthrough technologies, back-up options and potential breakthrough technologies**

Technology	Main advantages compared to reference	Potential drawbacks compared to reference	Technological maturity
	Steel Sector		
Coke-free steelmaking, with or without CCS (HIsarna)*	- 80% CO_2 reduction compared to average blast furnace with CCS, 20% without CCS - Lower investments and operational costs due to broader range of available inputs	- Needs replacement of existing blast furnaces	2010: Pilot phase (NL) 2025: Market deployment
Fastmelt process of direct reduction, with of without CCS*	- 55% CO_2 reduction compared to average blast furnace with CCS, 5% without CCS - Lower operational costs due to broader range of available inputs	- Needs replacement of existing blast furnaces - Higher investment costs	2010: Market deployment
Top gas recycling with CCS*	- 50% CO_2 reduction compared to average blast furnace - Expected to be the standard for newly built plants (retrofit option)	- Higher operational costs	2010: Pilot phase 2020: Market deployment
Electrolysis^	- Probably no carbon is needed in the production process		2010: not developed (pre-pilot phase)
	Cement Sector		
Magnesium based clinker (Novacem)*	- Over 100% CO_2 reduction compared to average kiln (sink). Avoidance of process emissions, carbonisation of product (no CCS required) - Same investment costs as alternative technologies and operational costs similar to average kiln	- There might be some issues with current market standards on product quality	2010: Pilot phase (UK) 2025: Market deployment
Oxyfuel firing with CCS*	- 90% CO_2 reduction compared to average kiln (almost complete CO_2 capture)	- Higher investment costs than alternatives and higher operational costs than average kiln	2010: - 2025: Market deployment
Biomass and natural gas utilisation	- 35% CO_2 reduction compared to average kiln	- Higher operational costs	2010: Market deployment
Higher use of Portland clinker substitutes	- 10 to 20% CO_2 reduction compared to average kiln	- Limited availability of substitutes	2010: Market deployment
	Paper and Pulp Sector		
Black liquor gasification, with of without CCS (Chemrec)*	- Over 90% CO_2 reduction compared to average production	- No impact on fossil fuel related CO_2 emissions in the paper sector.	2015-2020: Market deployment
Paper drying innovations^	- Would affect the most important source of non-biological CO_2 emissions in the sector		2010: not developed (pre-pilot phase)

Finally, top gas recycling is a technological route which has been explored at a LKAB pilot plant (Sweden). It will shortly be demonstrated on a commercial scale. The technology is more CO_2 efficient than the average blast furnace in Europe. New plants are expected to be built using this configuration.

In the longer run, electrolysis could be a promising option. It means that electricity is used for the reduction process. This would allow for carbon-neutral steel production if the electricity used in the process is produced without CO_2 emissions. The industrial process no longer requires carbon but electrolysis is still in the early stages of development. Without further R&D stimulation, it might, according to some, take over 20 years before the first commercial scale production facility could become operational.

Cement Sector

In the cement sector, the route of producing magnesium clinker based cement is identified as a promising future technology. In Europe it is currently being explored by Novacem (UK). The technology offers lower energy consumption and a huge CO_2 reduction, if not a carbon sink. Process emissions and carbonisation of product during production are avoided, so no CCS would be needed. At the same time cost figures are similar to the existing cement kilns. However, efforts need to be undertaken to make it ready for market introduction and for the products to (better) meet market standards.

In the meantime, the use of oxyfuel would be possible in the medium-term. It is an oxygen fired, limestone based clinker production process. This technology might yield up to 90% CO_2 abatement as it requires CCS. Both investment and operational cost figures are above average though.
Biomass/natural gas utilisation can be an option for companies to enhance their CO_2 efficiency somewhat (35% emission reduction expected). However, operational costs will be rather higher compared to the current average costs.

Finally, increased substitution of Portland cement could yield some CO_2 abatement. Due to a limited availability of alternatives, however, the degree of substitution might only increase from 20% (current EU average) to 35%. Subsequently, the emission reduction potential remains rather limited, i.e. 10 to 20%. Only when significant innovation regarding alternative binders takes place, the abatement potential of such technical option might increase.

Paper and Pulp Sector

Finally, in the paper and pulp sector black liquor[4] gasification with subsequent CCS has been identified as the technology that could be implemented in a relatively short term and allows for significant CO_2 reductions. This option has been developed by Chemrec (Sweden). This process may change chemical pulp production into a carbon sink by capturing CO_2 from black liquor for geological storage. It does require higher initial investment funds and probably somewhat higher operational costs.

If the paper sector wants to focus on CO_2 abatement in the production process, instead of applying CCS, a valuable or most relevant route would be drying processes. Drying of paper represents the bulk (up to 70%) of fossil energy consumption within the pulp and paper sector and subsequently represents the most important source of non-biological CO_2 emissions. In principle, the potential for energy saving in this process is still very high.

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[4] Black liquor is a major residue of chemical pulping.

Conditions for succesfull implementation

Technological innovation is crucial to realise significant CO_2 reductions up to 2050. In this study, we have already identified various promising initiatives. For a succesfull use of the technologies, it is necessary to stimulate (further) technical development and create market conditions with a preference for low CO_2 emission technologies.

In this regard, favourable market conditions are crucial. The prevalence of low energy prices has been an important aspect that has shaped the direction of technological developments so far. Innovation mainly focused on fossil fuel based processes instead of on alternative energy sources. This might change in the future when energy prices rise. Technologies based on renewable energy might become much more interesting for sectors to look at under that circumstances. The sufficiently high CO_2 price is also relevant for inducing further R&D on low carbon technologies. By creating a market for CO_2, the EU has created additional incentives to reduce emissions. It should ensure that the market keeps providing incentives to CO_2 reductions in order to stimulate innovation, in part by setting an ambitious emission reduction target. In some cases, additional regulation might be needed to stimulate the uptake of innovative technologies. For example by tightening BAT REFs for new plants.

In addition, further research is needed to make promising CO_2 abatement routes ready for market deployment. Therefore, the EU must (continue to) provide additional funds for R&D. In well functioning markets, one could argue, innovation will occur continuously. On the other hand, sectors might need additional support for investments in pilot plants and especially demonstration plants, which have a high capital requirement and represent significant risks (success is not guaranteed). Such funds have already been made available by the EU and several EU member states for demonstration projects in the steel sector, to be initiated as part of the ULCOS programme. Similar funding might be also be required in the cement sector for demonstration of the Novacem product and/or oxyfuel fired Portland kiln technology. In pulp production black liquor gasification and associated CCS might need further support. Also, targeted R&D programmes could increase the supply of new technologies. Options such as electrolysis and paper-drying innovations will require more effort and time to become technologically mature. They are still in a pre-pilot phase at the moment.

Finally, there might be a priority issue when a particular technology is scarce and can be applied in several sectors. For example, there seem to be limited storage locations for CCS that meet safety requirments[5]. The question is whether they should be reserved for industrial use instead of application in the energy sector (coal), where more CO_2 abatement options seem to be available.

Uncertainty

In this report we adopt a long-term perspective of technological innovations regarding CO_2 efficiency. We have painted a picture of promising technological options, based on our expertise, conversations with stakeholders and as much publicly available information as possible. Of course, it is always difficult to look at future developments. No one has a monopoly on wisdom there. The report provides indicative results and it reflects current knowledge on future developments and is therefore inherently beset by uncertainty. There is no guarantee that the technological routes we mention will actually be the ones

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5 Offshore storage and storage in deep (> 1 km) gas or oil that is located in non-tectonically active areas and are capped by a geological salt layer or geological layer of similar specifications.

that will have been realised in 20 or 30 years' time. The chance of actual realisation will depend on the pace of technological development in the coming years and the way governments design markets and stimulate innovation.

1 Introduction

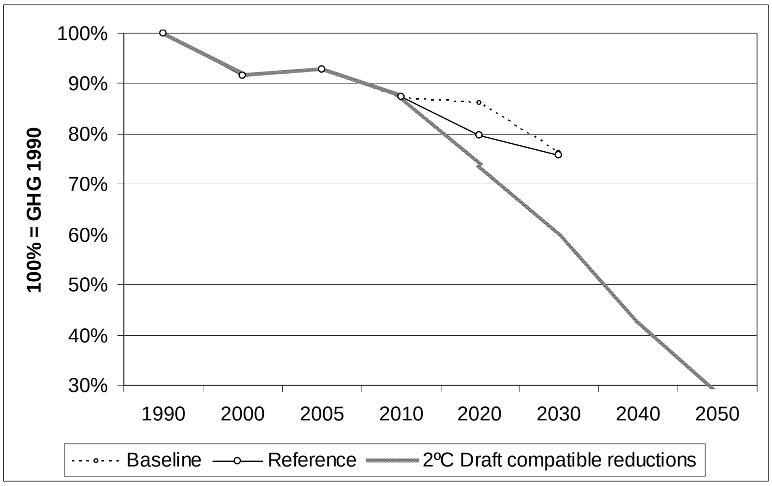
1.1 Background

Over the last few years, there has been much debate on the European policy package on Climate Change. It relates, among other things, to the overall reduction target on greenhouse gas emissions and the design of the emission trading system (EU ETS) which plays a prominent role for energy-intensive sectors. From 2013, the EU ETS foresees auctioning of emission allowances as the default option. However, it grants free allocation to many industrial sectors in order to address competitiveness issues and minimise the risk of carbon leakage. The aim is to base this free allocation on Community-wide ex-ante benchmarks that define emission levels per unit of product. For the amount of greenhouse gas emissions that falls within the benchmark, companies receive free allowances. The starting point for the determination of such benchmarks is the average performance of the 10% most efficient installations (2009/29/EC art. 10a). Currently, the debate centres on benchmark levels.

While stakeholders, media and politicians are particularly prone to focus on climate policy up to 2020, a longer-term vision is needed. In order to restrict the negative effects of climate change, the European Union has set the aim of limiting the average global temperature rise to a maximum of two degrees Celsius above the pre-industrial level, based on IPCC (2009). Achieving this concentration level requires a global reduction of greenhouse gas emissions of 80-95% in 2050 compared with the emission level in the period 1990.

Recent modelling estimates show that both baseline and reference scenarios for the EU's own domestic emissions are not compatible with the 2ºC trajectory (see Figure 1). Additional efforts will be needed, not only in the energy sector but in industrial sectors as well.

Figure 1 Short-term EU emission profile compared to 2ºC compatible long-term internal reduction trajectory (PRIMES/GAINS modelling)



Source: EC, 2010.

Note: Reference scenario is 20% reduction of internal emissions in 2020.

The challenge is, therefore, to move towards a low carbon, high-tech manufacturing industry. Innovation in CO_2 efficiency plays an important role here. The EU might want to take this into account when formulating climate policies. Therefore, CAN Europe has asked CE Delft to search for the technical opportunities that are/will be available in the region.

1.2 Aim

The objective of this study is to quickly scan technological developments in three industrial sectors and identify breakthrough technologies that are expected to yield significant reductions in industrial CO_2 emissions[6] in Europe. In the context of this study, we adopt the definition provided in Box 1.
The technologies might already be present in the market or are currently being demonstrated at pilot/industrial scale.

Box 1: Definition breakthrough technologies
Breakthrough technologies are, in the context of this study:
'Technologies that yield significant CO_2 reduction, will be widely commercially available in 2020–2030 at the latest and are economically competitive compared to reference and alternative technologies.'

The three industrial sectors that are covered in the analysis are:
1. Steel.
2. Cement.
3. Paper.

These sectors meet the four criteria set out in the next section. It will elaborate on the selection procedure and provide justification for our choice to focus on steel, cement and paper production.

1.3 Sector selection

Given practical constraints, only three sectors could be considered in this study. Subsequently, we needed to develop selection criteria to identify the most relevant sectors for this study. These are sectors that:
- Show significant CO_2 emissions – at least several (2-3%) per cent of total EU industrial CO_2 emissions – and produce those emissions by one process or a relatively limited number of processes.
- Breakthrough technologies are expected to be available.

1.3.1 Evaluation

Significant contribution
The steel and cement sector are the most relevant sectors in terms of the first criterion. The production of steel (and iron) is one of the most energy-intensive manufacturing sectors. It accounts for an estimated 5.2% of total global greenhouse gas emissions (OECD, 2005). Within Europe, its share in total industrial emissions is 21%. Table 2 shows industrial emissions for some individual sectors and their share in total EU emissions.

6 In the context of this study, CO_2 will be the most relevant greenhouse gas.

Table 2 EU industrial emissions as reported for 2007

	CO_2 emissions (Mtonne/year)			
	Fuel combustion	Process emissions	Total	% of EU total industrial emissions[7]
Refineries	**135**		**135**	**12%**
Iron and Steel	**137**	**96**	**233**	**21%**
Non-Ferrous Metals	**15**	**7**	**22**	**2%**
Chemicals	**82**	**43**	**125**	**11%**
Ammonia production	*9*	*28*	*37*	*3%*
Steam cracking	*38*	*16*	*54*	*5%*
…				
Pulp, Paper and Print	**41**		**41**	**4%**
Food Processing, Beverages and Tobacco (7 major sectors, number of smaller sectors**)**	**44**		**44**	**4%**
Cement	*72*	*108*	*180*	*16%*
Other Mineral Industry	**281**	**46**	**327**	**30%**
Ceramics	*20*		*20*	*2%*
Glass	*11*	*3*	*14*	*1%*
Lime Production	*11*	*26*	*37*	*3%*
Limestone and Dolomite Use		*11*	*11*	*1%*
…				

The criterion eliminates all products of manufacturing industries, all food industries and most of the chemical industry sectors. All these sectors are – in themselves - either too diverse and/or small or too energy extensive to be of significance to this project. The criterion has also been used to ignore the refinery sector. Though one of the largest sectors with respect to CO_2 emissions, it is also a sector with a wide variety of sources, e.g. distillation furnaces, boilers, cat crackers.

Technological innovation potential

Technical innovation potential refers to the possibilities that significant technological changes of products and processes can be realised.

We see that the paper industry has significant potential for technological innovation. There are potentially two fields for further development:

1. Utilisation of the lignine fraction that remains in the shape of black liquor after the Kraft pulping process.
2. Paper drying technology, the main source of fossil fuel related CO_2 emissions in the paper and pulp sector.

The potential of alternative feedstocks, which are still used in India for example, is unclear.

Utilisation of the lignine fraction in the feedstock (irrelevant for paper production) could open up possibilities for the production of chemicals now exclusively produced from crude oil. These might include:

– Chemicals based on the molecules present in the destroyed lignine, e.g. phenolic compounds, lignosulfonates (see Domsjo and Borregard cellulose plants).

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7 Power sector and mining not included.

– Chemicals or feedstocks produced by gasification of the destroyed lignine and utilisation of the syngas produced for Fischer Tropsch synthesis, methanol production or ammonia production.

On the other hand, the flat glass industry, wall-tile producing ceramics industries, inorganic industries and metal industries using electricity as chemical reduction agent seem to have little possibilities for technological innovation. This also applies to ammonia production and the processing of sulphide metal ores (zinc, copper, tin, lead, chromium, nickel). For most of these sectors, research into the development of alternative processes is limited, e.g. not a part of DG Research or DOE's Industrial Technologies Programme (ITP)(see EERE, 2009). For some sectors, alternative processes exist (e.g. Birkeland-Eyde process for ammonia production or the Deacon process for chlorine production) and in the past were breakthrough but have become outdated due energy inefficiency, technical problems (e.g. corrosion) and similar reasons. Alternative processes are being developed for aluminium (e.g. carbothermic reduction, kaolinite $AlCl_3$ reduction), but development is still in the R&D stage and has not been demonstrated on pilot or pre-industrial scale.

1.3.2 Selection

Based on the first criterium, we select the steel and cement sector as most relevant sectors. They have the highest scores on these criteria. We select the paper industry as the third sector for analysis in this project based on the second criterium. It has significant potential for technological innovation.

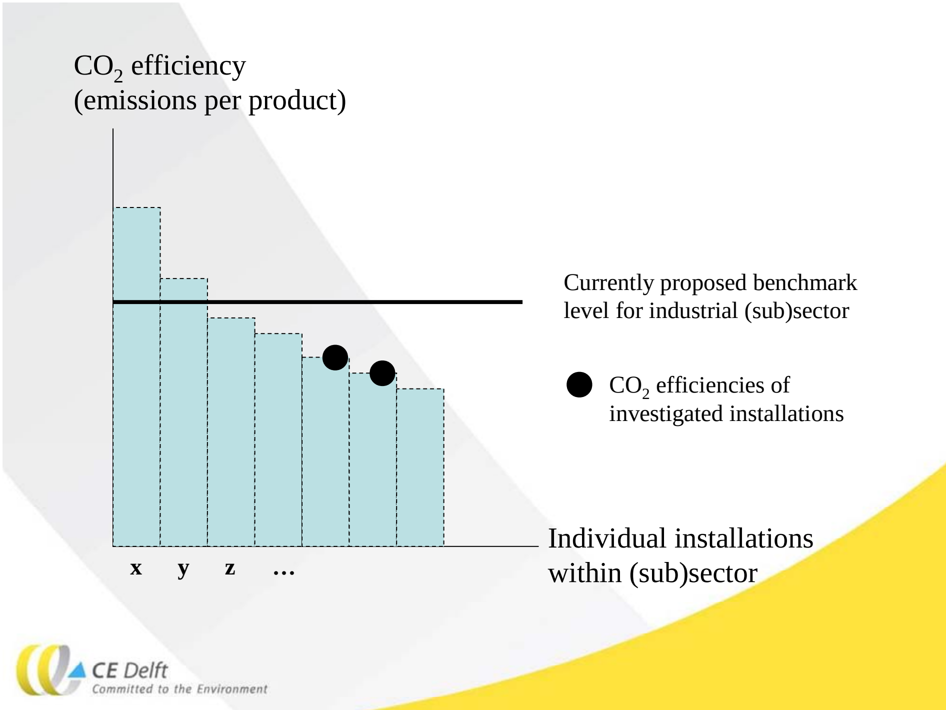
1.4 Analytical scope and results

In our search for breakthrough technologies that yield significant CO_2 efficiency improvements in the *longer run,* we focus on opportunities for new installations. These installations are relevant as they tend to have substantially better energy efficiencies than older ones. Besides, new entrants are crucial for the transition to a low carbon economy, whereas many existing installations are expected to be closed down before 2050. As in the energy sector, the technical lifetimes of installations are such that replacement would take place after 30-40 years of operation.

This does not mean, however, that there are no measures that can be implemented in existing installations to enhance their energy efficiency. In order to reach policy goals in the *short run*, energy-intensive industrial sectors have several measures at their disposal to reduce energy use and greenhouse gas emissions, and many such measures are also cost-effective in the sense that the payback time is less than five years. These 'generic' measures are available for a large range of energy consuming processes (such as highly efficient cogeneration of heat and power) as well as for specific industrial processes. However, those measures lie outside the scope of this study.

By providing examples of promising available or anticipated technologies, the report will offer further insight into the current debate on EU benchmarks that need to be developed. We will provide dots (see Figure 2) that reveal the CO_2 efficiency of individual installations or pilot plants. These will roughly indicate the future emissions reduction potential compared to the draft EU benchmarks (if available), which are shown for informative purposes. The report does not aim to provide an alternative benchmark level, as the examples might or might not represent the sector-wide benchmark level line.

Figure 2 Type of project results



Note: This figure is solely drawn to illustrate with *type* of results are to be expected. It is not meant to reflect project results with respect to content.

1.5 Approach

In this project, three tasks are performed;

1. Rough sector analysis, including an evaluation of technological developments in each sector.
2. Inventory of environmental and market performance of technologies.
3. Identification of breakthrough technologies.

The different tasks are described in more detail below.

1.5.1 Rough sector analysis

For each sector, an introductory description of product market(s) and production process is provided. Broad energy consumption, total sectoral CO_2 emissions are also sketched, based on publicly available data, as well as the average and lowest specific CO_2 emissions (the emissions per unit of product or semifinished product.

Subsequently, we outline current technological developments with respect to energy efficiency and CO_2 emissions. An inventory of promising technologies in the future is made by evaluating existing R&D programmes and roadmaps to sustainable manufacturing currently under development. We will look at possible routes that are being investigated within the EU and technical developments outside the EU. There might be relevant opportunities originating from the non-EU region that will be become available to EU manufacturers as well. There is little reason to suspect that technology will not be shared internationally. Finally, the future prospects are presented of a promising technology which is undergoing further development at the moment.

1.5.2 Inventory of environmental and market performance of technologies

After making an inventory of technological developments in each sector, we evaluate the environmental and economic performance of relevant technologies under consideration:

- Environmental performance
  The impact a particular technology is expected to have on energy consumption (fuel and/or electricity use) and on (indirect) CO_2 emissions per unit of product is estimated[8]. For cement and steel production this is relatively uncomplicated, as they involve rather straightforward production process with a limited number of abatement options. The paper sector is more heterogeneous, with significant variations in types of installations and products.
- Economic performance
  Whether or not a technology will be implemented in practice is highly dependent on its competitiveness with respect to the commonly applied technology or alternative routes. Therefore, the capital investments needed to build a new plant (CAPEX)[9] and operational costs (OPEX) are indicated.

Since most of the technologies under consideration are still in pilot or development phases, we will describe the performance based on the estimates provided compared to a reference technology. This will be the average EU installation which is currently operational. It is relevant to look at such existing plants as they are responsible for the CO_2 emissions at the moment and in the near future, depending on when re-investment or replacement takes place. In addition, the performance of a newly built installation with more or less the 'conventional' technology (f.e. an upgrade) is mentioned. This comparison shows what the application of a new technology has to offer compared to staying on the current technological path. estimate.
The analysis is based on publicly available information and data provided by the selected companies/installations.

[8] Issues of labour intensity and footprint/space requirement have been evaluated. Since hardly any differences have been found, the findings are not included in texts and tables.

[9] Recall that we will focus on new plants (see Section 1.4).

It is worthwhile noticing that the economic costs of CO_2 efficiency are not the only characteristics that determine whether a particular technology will become a success of failure. Even when CO_2 efficiency can be reached by technologies or cost benefits are present, there might be other issues that are relevant for market implementation. If, for instance, the product quality that can be obtained by the new production process is different and markets first need to adapt their standards. Also, there might be problems with the societal acceptance of certain technologies. For example, the application of CCS is controversial and partly needs further demonstration.

1.5.3 Identification of breakthrough technologies

Breakthrough technologies will be determined per sector. A technology is classified as 'breakthrough' when it meets three criteria (also see Box 1 in Section 1.3):

- Significant CO_2 emission reduction
  Given the ambitious long-term climate goals, a breakthrough technology should ideally have a CO_2 emission that is approximately 90% lower than that of the current average technology applied in Europe[10]. The option of CCS is included in the analysis, but it is also worthwhile to consider other, sector-specific technologies that significantly improve the CO_2 efficiency of the particular industrial processes instead of capturing the resulting CO_2. In practical terms, this means that process innovation technologies seem more promising ex-ante than retrofit options since they are like to abate a larger pportion of process emissions. Therefore, we think it appropriate to set the criterion for 'breakthrough' technologies at an emission reduction level of over 25% compared to the reference scenario.
- Commercial available in 2020-2030
  The technology should become technically available at industrial scale in the period 2020-2030 in order to have the potential to stimulate a timely transition to a low carbon economy. Given general patterns of R&D, this would at least require a pilot plant in 2010. The R&D route might take several years. Usually a pilot phase, in which the technology is firstly made operational and tested, is followed by a demonstration plant whose capacity is of (almost) industrial scale. If the technology turns out to be successful at this stage, it can be made ready for broader market introduction. The technique should allow for broad roll-out within the sector.

[10] Current average technology refers to the technology currently applied in the considered sectors. Descriptions of applied technology can be found in the IPPC BAT REF documents of the considered sectors.

- Competitive with respect to current/alternative technologies
  In order to have a chance of succesfull market implementation, it is important that technologies compete with commonly applied and alternative technologies. Ideally, it would have the advantage of lower production costs. This relates to capital investments needed to built a new plant (CAPEX) as well as operational costs (OPEX); the latter costs could be reduced due to lower energy requirements. European industry already faces relatively high energy prices and prices are projected to rise in the future (PBL, 2010)[11]. It should be emphasised here that in evaluating the cost-effectiveness of breakthrough technologies account must be taken of *future* market conditions upon implementation. When energy prices rise, as most economic modelling suggest, due to higher oil prices and also in response to stringent climate policy, it becomes crucial to enhance energy efficiency.

Some technologies might not meet the abovementioned criteria. Instead they might fit the classification of:

- Back-up technologies
  These are technological options which certainly fit in available production processes but do not yield the required CO_2 reductions and/or come at higher costs. They might still be needed in case a particular breakthrough technological innovation eventually turns out to be less successful than expected. In addition, not all existing plants will have been replaced by 2050 and, in the meantime, implementation of some efficiency-enhancing measures might be desirable. Therefore, we have also mention back-up technologies that enhance the CO_2 efficiency of existing technologies.
- Potential breakthrough technologies
  These technological routes might turn out to be longer-term breakthrough technologies (beyond 2030-2050) if additional R&D is stimulated. They are not in the pilot stage yet or are being applied in other sectors than those considered in this study.

With regard to the types of technologies that can be applied we distinguished between:

- Use of energy carriers with a lower carbon intensity in existing technology, e.g. electricity or biomass instead of natural gas or coal.
- Combination of existing technology with capture of produced CO_2 for perpetual deep geological storage.
- Design a new process which is intrinsically more energy efficient and/or carbon-neutral.

[11] Please note that production costs are just one aspect of competitiveness. The degree to which product differentiation can be enhanced also influences the competitiveness of certain technologies. Since industries in the EU have to deal with relatively high labour costs, high energy prices and the fact that most raw materials have to be imported, EU based industry has to offer other advantages compared to competing regions. Strengths are the high quality of products, aided perhaps by a green corporate image. Since many technologies are still in R&D phases, and available information is limited, this study will only look at production cost estimates.

1.6 Data availability

The execution of this project has been conditional on the availability and reliability of data on the evaluated technologies that are at different stages of development. Some published information on energy consumption, CO_2 emissions and costs consist of early results stemming from pilot phases whereas other technologies are already on the market and figures are less uncertain. Besides, strategic behaviour in the provision of data might play a role. Companies might have an incentive to be optimistic on CO_2 efficiency, as they want to present themselves as frontrunners. On the other hand, stakeholders might be more negative on attainable CO_2 efficiency in the sector in the light of the broader political context (for example, debates on benchmarks). The figures in this report are based on the best information available at the moment of writing.

1.7 Structure of the report

Chapters 2, 3 and 4 will cover the three sectors under consideration: steel, cement and paper respectively. Chapter 5 will form the conclusion. Conditions that must be met for succesfull implementation of technological innovations are mentioned here.

2 Steel sector

This chapter considers innovation in the steel sector. A brief introduction to the sector is provided in Section 2.1, covering some basic information on the steel market, products and production process. Section 2.2 describes CO_2 emissions and energy consumption. Subsequently, Section 2.3 goes into the current technical developments, after which Section 2.4 looks at potential future alternative routes. Breakthrough technologies are then identified in Section 2.5. This chapter is concluded with Section 2.6 with an overview of the findings. The economic and environmental performance of the evaluated technologies are summarised and a table lists the main characteristics of the breakthrough technologies showing their main strengths and weaknesses.

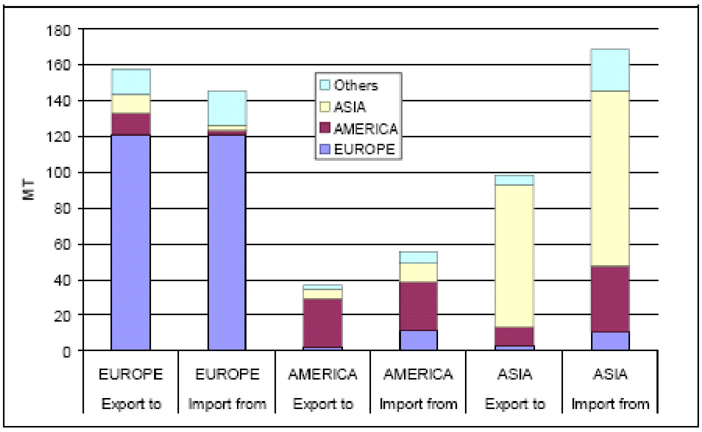
2.1 Introduction to the sector

2.1.1 Market outline

Over recent decades, global (crude) steel production has grown rapidly, amounting to 1330 million tonnes in 2008 compared to 790 million tonnes in 1999 (WSO, 2010). Production has increased especially in emerging markets such as China. This country is the largest producer, covering nearly 38% of the market, followed by the EU with a share of 15%. Current turnover in the EU steel sector is approximately € 150 billion. The sector employs 410,000 people, representing 1.25% of the total employment in EU manufacturing (EC, 2009a).

Steel is heavily traded with about 40% of production traded globally. Although such trade mainly takes place within regions (see Figure 3), there is also some trade between different regions. The EU has become a net importer in recent years. Today the EU is the world's third biggest exporter and primary importer. China is the biggest supplier followed by Russia and Ukraine. The EU imports more than 90% of its needs of primary raw materials, iron-ore and coking coal.

Figure 3 Steel trade across regions by volume



Source: Climate Strategies, 2007.

The European steel sector is a modern industry with its main customer base found within its home markets, particularly in the high-end segments. The main competitive strength is based on high quality products, product innovation and technological development, efficiency and skilled manpower. After all, steel is a heterogeneous product. There are variations in steel grades and qualities to satisfy a wide range of applications, including the construction, automotive, packaging and manufacturing industries. These differences may constitute a kind of protection barrier against the hardships of the global market, especially for flat products demanded by the automotive industry and for cans. In the EU, products and production methods are generally advanced compared to other regions. Nevertheless, such an advantage may vanish in the medium-term as technology quickly spreads (Hatch Beddows, 2007).

For products in the construction segment, the situation is different as they would require a more uniform quality which other regions can also meet. Subsequently, Europe might face more international competition here. European steel producers are being increasingly confronted with new competitors on the world market (China, Brazil, India and the Commonwealth of Independent States (CIS) countries). The steel sector emphasises the fear of losing international market competitiveness when climate policies become tougher. In this regard it should be mentioned that an increase in competitive pressure would not necessarily mean that companies are unable to pass CO_2 costs on to consumers through price increases (see CE, 2010). They might opt for higher prices to maintain profit margins, thereby accepting a potential drop in market share. Yet, non-EU import ratios have been relatively low given the given the difference in operating costs observed throughout the world[12]. The average BOF Western EU plant has 40% higher operating costs than Brazil and Russia. This gap falls to around 20% for India and China (Climate Strategies, 2007)[13]. This might indicate that the European steel market seems to be somewhat protected from foreign imports through trade barriers.

2.1.2 Production process

The most significant production route for steel from ore is the Blast Furnace (BF) and associated Basic Oxygen Furnace (BOF) production processes (see Figure 4) that cover approximately 2/3 of total worldwide and European steel production. Only a small amount of primary steel was produced via alternative routes, direct reduction processes with subsequent processing of produced sponge iron in an Electric Arc Furnace (EAF). These alternatives have consequently been ignored in this chapter[14].

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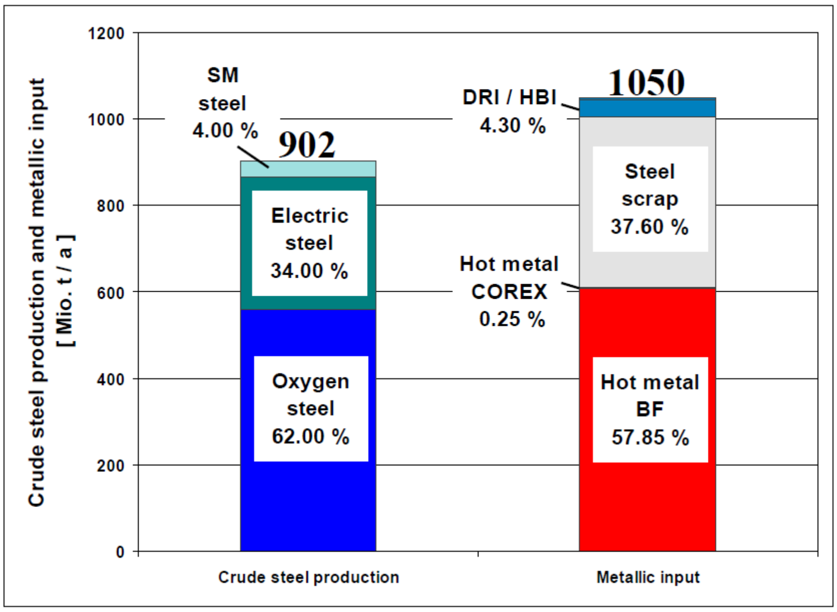
12 Although at the moment, due to the economic crisis, steel is dumped on EU markets by countries like Russia and the Ukraine which have overcapacity.

13 Concerning the EAF plants, operating costs vary much less among regions (Climate Strategies, 2007), so low trade intensities are not striking as far as cost differences are concerned.

14 Another reason for ignoring these processes is that since in almost all direct reduction processes the ore is not melted and no slag is produced the majority of impurities (sulphur, gangue constituents) are still present in the produced sponge iron. In order to enhance EAF steel quality, the ore must contain low grades of impurities (< 5% weight), which, in practice, results in a restricted applicability of this kind of processes.

Figure 4 **Total global steel production**



Source: Schmöle and Lüngen, 2004.

Note: The left bar represents the total global production of refined steel, the right bar represents the raw materials processed.

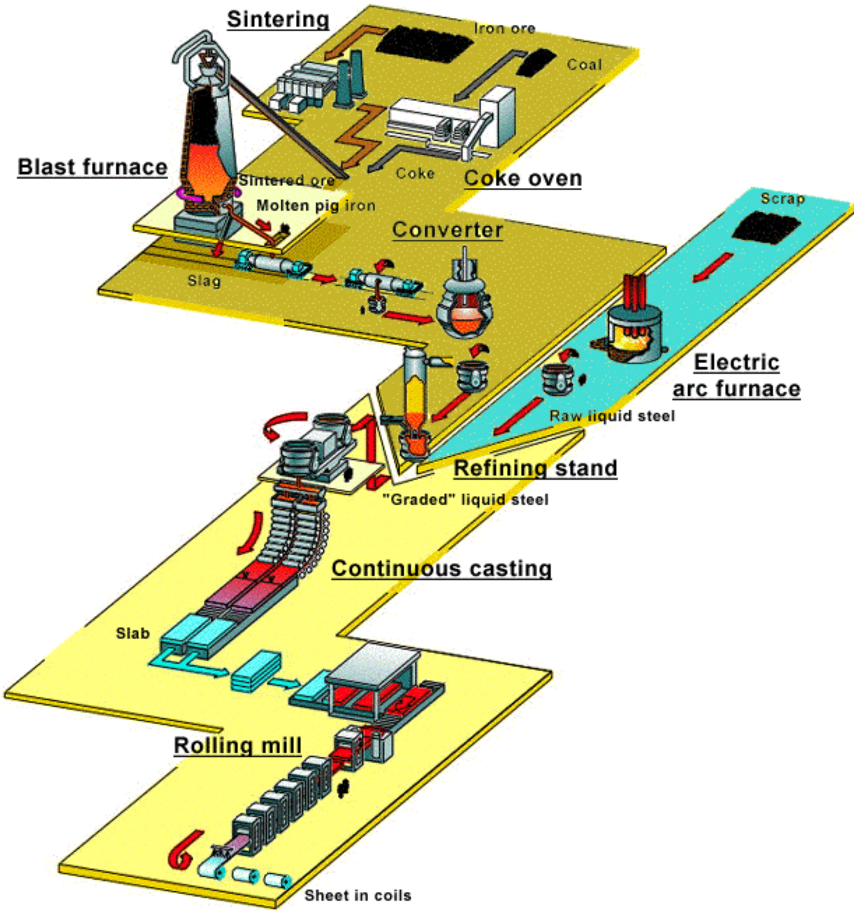
About 1/3 of the global steel output originates from scrap recycling in Electric Arc Furnaces (EAF). Such secondary steelmaking is about 4.5 times less emission intensive than the BOF process (see Section 2.2). Since its application is limited by the availability of scrap and its relevance is less in terms of emission reduction, no further account is taken of this route in this study.
In conventional ore based iron making via the blast furnace – converter process route (Figure 5), finely ground ore is mixed with limestone, coke breeze and iron containing process residues and is agglomerated at high temperature into sinters. In parallel coking coal is converted by pyrolysis into coke oven gas (COG), coke and breeze, the required process heat being supplied by burning part of the produced COG.

Coke and sinters are fed to the blast furnace together with oxygen-enriched hot air and pulverised coal. There the oxygen-enriched air reacts with coke and pulverised coal to produce synthesis gas, which subsequently reduces the iron oxides in the sinters. Carbon is only needed to fuel a chemical reaction.

Molten pig-iron, containing 4-5% Carbon, and molten slag are tapped from the furnace. The remaining blast furnace gas is utilised as a fuel, for example, to preheat the enriched air.

The molten pig-iron is next refined in the basic oxygen furnace in which oxygen is blown through the melt to oxidise the dissolved carbon. In this step the remaining impurities are removed and alloying elements added to adjust material specifications. The hot refined steel is cast into slabs, which are next rolled into smaller thickness.

Figure 5 Process of making steel via the blast furnace - converter process route



Source: Schabrun, 2002.

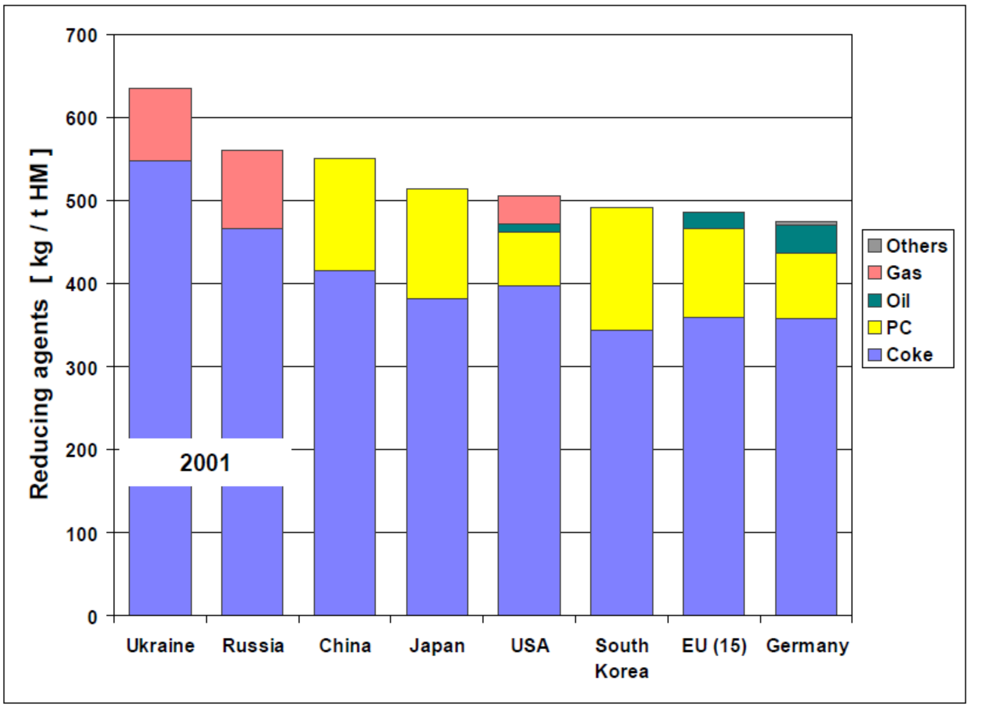
2.2 CO_2 emissions and energy consumption

As mentioned before, the production of steel is among the most energy-intensive and, subsequently, CO_2 emitting sectors. It accounts for an estimated 5.2% of total global greenhouse gas emissions (OECD, 2005) and 21% of total EU industrial emissions (see Table 2 in Section 1.3). About 80-90% of these emissions are related to the blast furnace converter process.

The size of the CO_2 emission per tonne of hot metal is related to the required amount of reduction agents and the carbon intensity of the applied agents. Additional CO_2 emission results from limestone calcination in sintering or when limestone is used as flux.

Current consumption of reducing agents for the blast furnace – converter route in the EU-15 amounts to 490–470 kg/tonne hot metal (HM) and consists of coke, pulverised coal and a small amount of fuel oil. Other types of reducing agents applied in practice are natural gas, biomass and secondary fuels, e.g. waste plastics.

Figure 6 Reducing agents consumption[15]



Source: Schmöle and Lüngen, 2004.

Associated CO_2 emissions for the consumption of reducing agents per tonne of hot metal (HM) in the EU-15 amount to approximately 1.65 tonnes/tonne hot metal, including coking, sintering and decarbonisation related emissions.

In several studies[16] it is stated that the EU blast furnaces are already operating near the ideal process conditions and that room for improvements within the process are limited. The proposed benchmark levels for coking, sintering and hot metal production give an overall emission per tonne of hot metal of 1,460 kg CO_2 eq./tonne of hot metal (Ecofys et al., 2009)[17], approximately 12% lower than current average EU-15 emission level and comparable with the optimum level.

15 Though the figures in the illustration are somewhat outdated (2001), we think they are still relevant, given total CO_2 emissions per unit of hot metal.

16 See e.g. BAT REF steel, 2001; Ecofys, 2009a; Schmöle and Lüngen, 2004.

17 The benchmarks are 90 kg CO_2 eq./tonne coke, 119 kg CO_2 eq./tonne sinters and 1,286 kg CO_2 eq./tonne hot metal. Ratios mentioned in the BAT reference document are 360 kg coke/tonne hot metal and 1,160 kg sinters/tonne hot metal. Total emissions amount to 90 x 360 + 1,160 x 119 + 1,286 = 1,456 kg CO_2 eq./tonne hot metal.

Alternative reducing agents are applied additional to cokes as illustrated in Figure 6. Natural gas or biomass might (partially) substitute pulverised coal injection and fuel oil injection. Complete substitution of pulverised coal and fuel oil by natural gas or biomass respectively would reduce net greenhouse gas emissions by 10% and 15% respectively compared to the current average EU-15 emission level of 1,650 kg CO_2/tonne of hot metal.

2.3 Current technological developments

In the steel sector, there are broadly three potentialtechnological directions for realising a significant reduction in CO_2 emissions:

- Design a new process which is intrinsically more energy efficient and/or carbon-neutral.
- Low carbon reducing agents and fuels.
- CO_2 capture and storage.

These options are being developed, both within and outside the EU.

An EU initiative is the Ultra Low CO_2 steelmaking programme (ULCOS) that consists of 48 partners from almost every European country and is supported by the European Commission. Under this programme, a consortium of EU based steel producers (under the leadership of ArcelorMittal, ThyssenKrupp and Tata Corus) has been developing new technologies for steel production, each technology being in a different development stage (see Figure 7):

- Blast furnace top gas recycling (TGR), recycling of blast furnace gas after CO_2 has been removed from it.
- Coke free steelmaking[18] process developed from Corus cyclone melting technology and Rio Tinto Hismelt bath smelting technology (HIsarna).
- Direct reduction of iron-ore with natural gas (ULCORED), producing hydrogen as a by-product.
- Iron-ore electrolysis (ULCOWIN).
- Hydrogen and biomass based steel production.

These processes were selected on the basis of the technological inventory during the first phase of the ULCOS programme (ULCOS I, 2004-2010).

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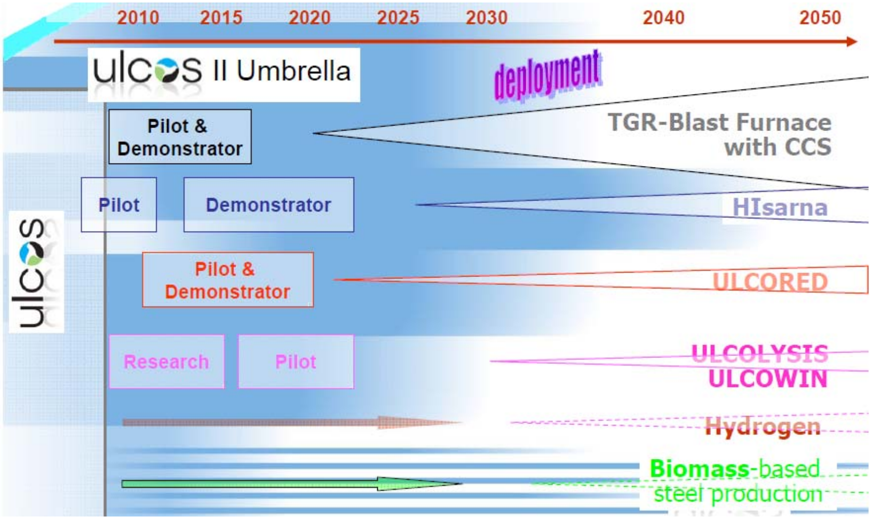
18 Meaning that coal is used directly.

Figure 7 **Time table of ULCOS technology development**



Source: Birat, 2009b.

Current developments, within the next phase of the programme (ULCOS II, 2010-2017), focus mainly on two routes: TGR and HIsarna. Demonstration projects have been announced and project funds have been reserved for both technology development paths[19]. These technologies can be developed within the medium-term, contrary to the still very experimental electrolysis process. TGR and HIsarna also match better with current EU coal based production practices than natural gas based direct reduction. Hydrogen and biomass based steel production have not been selected as a focus of the ULCOS project, partly due to the disputable sustainability of biomass. The extent to which these alternative technological routes (such as electrolysis) might become valuable options in the much longer run is discussed in Section 2.5.

Outside the EU, the only new technologies with reduced energy consumption and associated CO_2 emissions capable of utilising low-grade ore are the HIsmelt process and the Kobe steel Fastmelt process. The first is now being integrated in the HIsarna process development under the ULCOS II programme so no further consideration is given to it in this report.
The next sections describe the three identified technologies:
- Coke-free steelmaking (HIsarna).
- Fastmelt process of direct reduction.
- Top Gas recycling.

After a short introduction on the stage of development and applied technology, we look at strengths and weaknesses. Based on the available information, we have estimated production capacity and extracted the relative energy consumption volumes, CO_2 emissions and economic parameters for each technology compared to the reference technology (see Section 1.5.3).

19 For example, TGR will be demonstrated on a small scale at ArcelorMittals Eisenhüttenstadt blast furnace 3 and if trials are successful will next be demonstrated at large-scale capacity at ArcelorMittals Florance blast furnace 6. The European Commission has authorised an investment aid of € 30.18 million granted by Germany to ArcelorMittal Eisenhuettenstadt's TGR project.

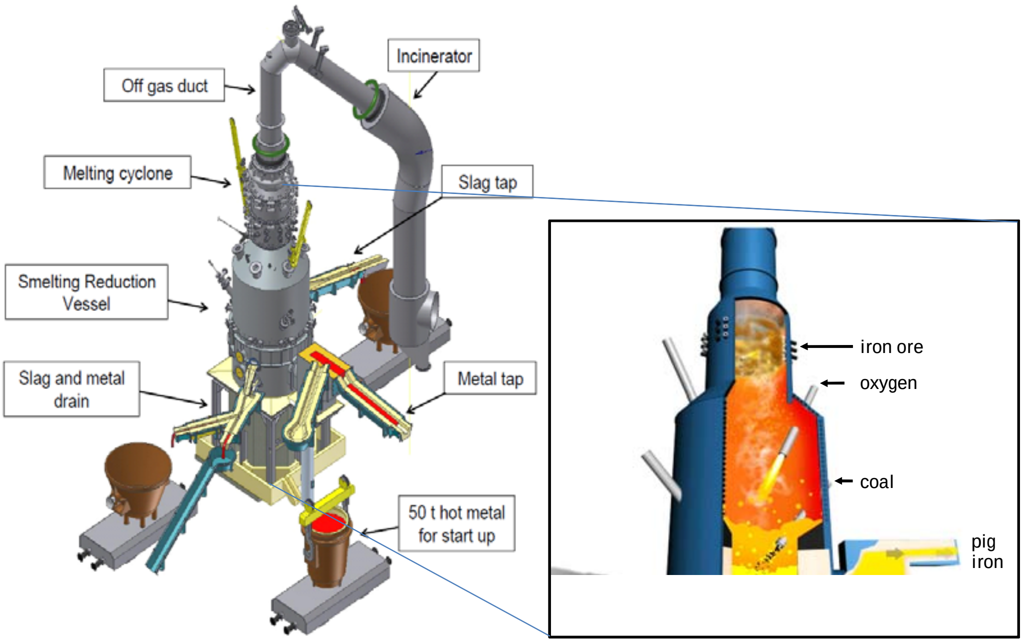
2.3.1 Coke-free steelmaking

Introduction
The process of coke-free steelmaking (HIsarna) is in the pilot phase at the moment. It will first be demonstrated in a 60,000 tons/annum pilot installation currently being built at CORUS IJmuiden (the Netherlands) and planned to commence operations this summer.[20] Further development may include a 700 kton/annum commercial scale plant, which will be designed in the period 2015/2016 (based on the experiences with the pilot plant) and constructed between 2017/2018.

Ultimately, the HIsarna technology will probably be applied in the market at a 500–1,000 ktonne/annum scale, which complies with the requirements for medium scale and flexible production capacity in the steel sector[21](Meijer, 2010).

Technology
The HIsarna technology combines a melting cyclone for ore melting and the Hismelt smelter vessel for final ore reduction and iron production. The smelter vessel has been proven on commercial production scale, the cyclone on pilot scale. The combined process is approximately 20% more energy efficient and produces less greenhouse gas emissions per tonne of hot metal compared to current average blast furnace technology (see Table 3) primarily because it does not require ore sintering and coke production. The hot metal produced will be processed into steel in a conventional BOF.

Figure 8 Illustration of the HIsarna process



Source: Birat, 2009 and Link, 2008.

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20 The Dutch Cabinet of Ministers approved on November 27, 2009 a € 5 million contribution to the project. The rest of the investment will come from European Commission research funds and from the ULCOS consortium partners.

21 Blast furnaces in general and especially integrated steel plants including blast furnaces, sinter plants, coke plants and basic oxygen furnaces require production capacities of 3 Mtonnes of hot metal and more to be competitive. Such a production capacity represents a large and often prohibitively large investment.

Coal preheating and partial pyrolysis in a separate reactor can be added as a third step for the further optimisation of energy efficiency. Biomass could be utilised as reducing agent after partial charring. Volatiles in reducing agents (coal, biomass, others) negatively impact process proceedings[22]. The HIsarna technology allows for processing a wider range of ores compared with the TGR blast furnace process, including ores containing phosphorous and alkali metals. With both the TGR as the HIsarna routes a reduction of 50% or more can be realised only in combination with CCS and/or the use of biomass as a reducing agent.

Strengths and weaknesses

With respect to environmental performance, implementation of HIsarna technology is expected to yield a CO_2 reduction of 20% compared to the average blast furnace in Europe. Its CO_2 emissions are about 330 kg/ton hot metal. When combined with CCS, reductions of up to 80% of emissions are expected to be achievable.

Looking at economic aspects, HIsarna will require significantly lower capital investment costs (CAPEX) and will produce semi-finished products with the same quality as current breakthrough technology at significantly lower operational costs (OPEX), including reduced energy consumption. HIsarna will be capable of utilising a wider range of (lower quality) feedstocks. Please note that both CAPEX and OPEX refer to production of pig-iron. For the blast furnace route both include coke plant and sinter plant costs.

The results are summarised in Table 3.

[22] No information has been found about the effects of this addition on process efficiency and specific CO_2 emissions

Table 3 **Economic and environmental performance of HIsarna compared to the current average technology for pig-iron production**

	Current EU average blast furnace	HIsarna*
Production capacity (Mtonne HM/year)	0.5-5.0	0.5-1.0
Energy consumption	100% (± 17 GJ/tonne HM)	80%
CO_2 emission tonne/tonne HM[23]		
- With CCS:	1,650	330 (-80%)
- Without CCS:	1,650	1,320 (-20%)
CAPEX[24]		
- Greenfield	100%	75%
- Brownfield	-	65%
OPEX (incl. energy, excl. depreciation costs)	100%	90%

Sources: Linkm, 2008; Meijer, 2008.

Notes: The percentages should be interpreted as relative scores, as the performance of the reference average blast furnace is set at 100%. The other data are absolute figures.

HM = Hot metal (or pig-iron).

A potential practical drawback is that the penetration of HIsarna in the EU steel sector might be limited as increases in steel consumption in the EU are marginal and can still be met by increasing the productivity of existing blast furnaces. Furthermore, steel producers tend to overhaul the existing blast furnaces every 15 years or so to increase plant's lifetime. Costs amount to approximately 50% of the investments for a new blast furnace. As a consequence of both mechanisms, the rate of replacement of existing facilities is expected to be slow and determined by existing blast furnaces reaching the end of their lifetime. Opportunities for new plants will mainly be related to substitution of blast furnaces in existing integrated steel plants where one of the individual plants is at the end of its lifetime and further overhaul possibilities exist. Increasing the pace of replacement will require additional legislation, e.g. tightening the BAT REF standard for oxygen steel production after the HIsarna technology has been proven to be commercially mature (see Section 5.3).

23 This figure only covers direct CO_2 emissions. This applies to all tables provided in the report.

24 A greenfield site refers to a new industrial location without any infrastructure and other facilities and utilities. As a result investments for these issues have to be made too (so-called indirect investments). As reference a ± € 750 m/Mtonne production capacity is chosen.
A brownfield site refers to an existing industrial site where these indirect investments have been made in the past.

2.3.2 Fastmelt process of direct reduction

Introduction

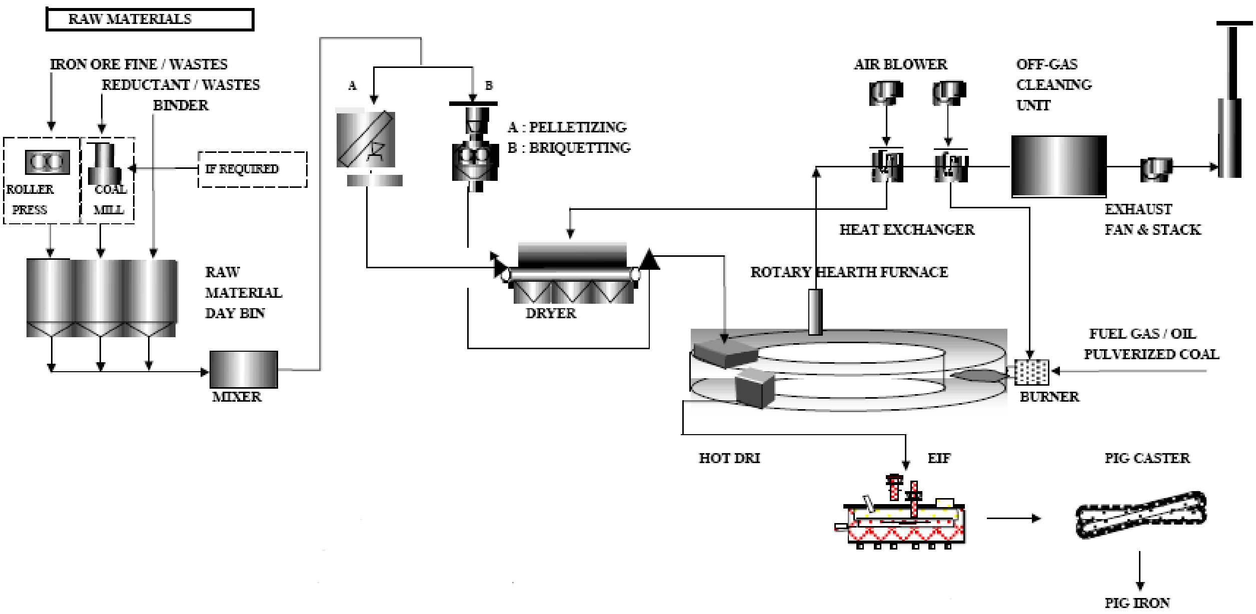
The second process, the Fastmelt process may be implemented at commercial-scales of up to 500 ktonnes/year in the short term:

- The rotary hearth furnace is being demonstrated on a commercial scale of 500 ktonnes/annum by Mesabi in Hoyt Lakes, Minnesota (USA).
- Processing of cooled direct reduced iron is common practice.
- Hot charging of electric furnaces – for the reduction of electricity consumption - has been common operational practice at some EAFs.
- A coal-fired melting furnace has been demonstrated at a production capacity of 16 ktonnes/tear by Midrex. However the Hismelt process – a similar process - is operationing at a capacity of 800 ktonnes/year.

Technology

The fastmelt process combines a rotary hearth furnace with a melting furnace. Fine ore and pulverised non-coking coal are together consolidated by pelletising or briquetting. The briquettes or pellets are next heated by fuel gas combustion up to a temperature (± 1,3502 ºC) at which the coal reduces the iron oxides in the ore. Fuel gas demand is mainly covered by CO produced in the reduction reaction. The hot reduced iron pellets or briquettes are next fed to a melting furnace where they become molten. The required heat is provided either by electricity or by coal combustion with oxygen. Any remaining iron oxide is reduced and gangue is separated as slag.

Figure 9 The fastmelt process flow sheet



The fastmelt technology is capable of processing similar ores and utilising similar coal qualities as the HIsarna process. Direct energy consumption of the process seems to be comparable to 10% lower than consumed on average by an EU blast furnace[25]. We would expect CO_2 emissions to be 80% lower when the process is combined with CCS. However, according to (Link, 2008) the maximum reduction that can be achieved with CCS is 55% compared to current average blast furnace process. We used the latter figure.

Strengths and weaknesses

The technology is capable of processing a wider spectrum of ores and ores of lower quality compared to the blast furnace process. The rotary hearth furnace does not require cokes as a reducing agent. Both characteristics result in significantly lower operational costs, as Table 4 indicates. Energy consumption and CO_2 emissions are slightly lower to or comparable with the blast furnace process. Specific investment costs for the fastmelt process and associated electric arc furnace are significantly higher compared to large integrated and blast furnace based steel plants.

Table 4 **Environmental and economic performance of the fastmelt process compared to the current average technology for pig-iron production**

	Current EU average blast furnace	Fastmelt*
Production capacity (Mtonne HM/year)	0.5-5.0	0.5-1.0
Energy consumption	100% (± 17 GJ/tonne HM)	95-85%
CO_2 emission tonne/tonne HM - With CCS: - Without CCS:	 1,650 1,650	 760 (?) (-54%) 1,590-1,420 (-5%)
CAPEX[26] - Greenfield - Brownfield	 100% -	 200% - no CCS (?)
OPEX (incl. energy, excl. depreciation costs)	100%	80-90% (?) – no CCS

Sources: Link, 2008; Meijer, 2008.

Notes: The percentages should be interpreted as relative scores, as the performance of the reference average blast furnace is set at 100%. The other data are absolute figures.

HM = Hot metal (or pig-iron).

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25 The process consumes 420 kg metallurgic coal (12 GJ), 2.5 to 2.7 GJ natural gas or LPG and at least (hot charge of reduced iron, high level of carbon in reduced iron) 350 kWhe (1.3 GJ) per tonne hot metal.

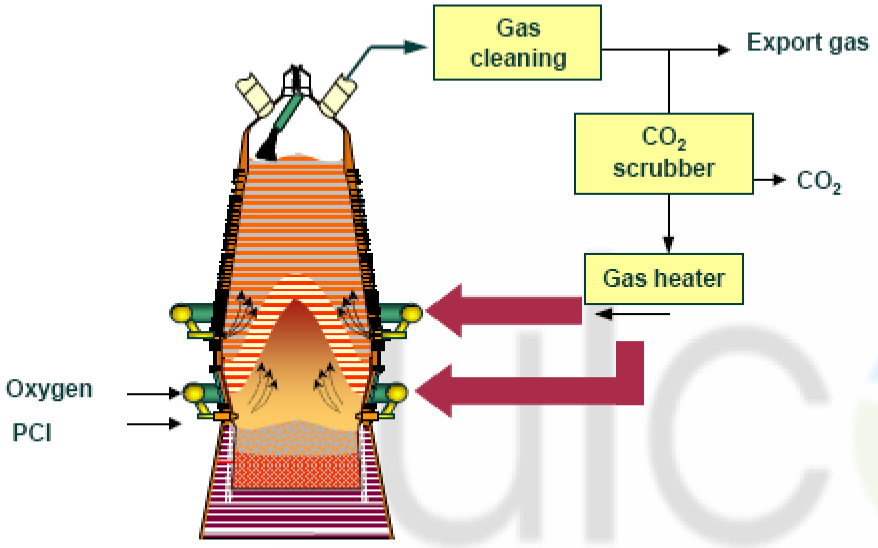
26 A greenfield site refers to a new industrial location without any infrastructure and other facilities and utilities. As a result investments for these issues have to be made too (so-called indirect investments). As reference a ± € 750 m/Mtonne production capacity is chosen. A brownfield site refers to an existing industrial site where these indirect investments have been made in the past.

2.3.3 Top gas recycling

Introduction
Top gas recycling has been demonstrated at the LKAB research plant in Sweden. It is an option for new plants and a retrofit option for existing blast furnaces.

Technology
In the process the CO_2 and CO-rich blast furnace gas is separated with a VPSA[27] into CO_2 and CO + N_2. The CO-rich stream is recycled to the blast furnace and used as reducing agent, increasing the efficiecy with which coal is used in the process. The CO_2 can be purified, i.e. pre-treated, liquefied and compressed for deep geological storage.

Figure 10 Top gas recycling process



Source: Birat, 2009.

Strengths and weaknesses
The TGR process does not give a net reduction in energy consumption as reduced coke consumption is balanced by an increased electric power requirement for CO_2 separation. Greenhouse gas emissions are reduced if CO_2 is sequestered. Table 5 shows indicative figures for the environmental and economic performance of a blast furnace with TRG configuration compared to the average blast furnace in Europe. The figures represent the basic configuration for the process. With additional features, installations might be able to achieve additional emission reductions (Birat, 2010).

27 VPSA = Vacuum Pressure Swing Absorbtion. PSA refers to a process in which gases are separated by their different affinity for absorbtion in a molecular sieve, which is next regenerated by lowering the pressure. In the case of a VPSA a vacuum is created for regeneration.

Table 5 **Environmental and economic performance of TGR compared to the current average technology for pig-iron production**

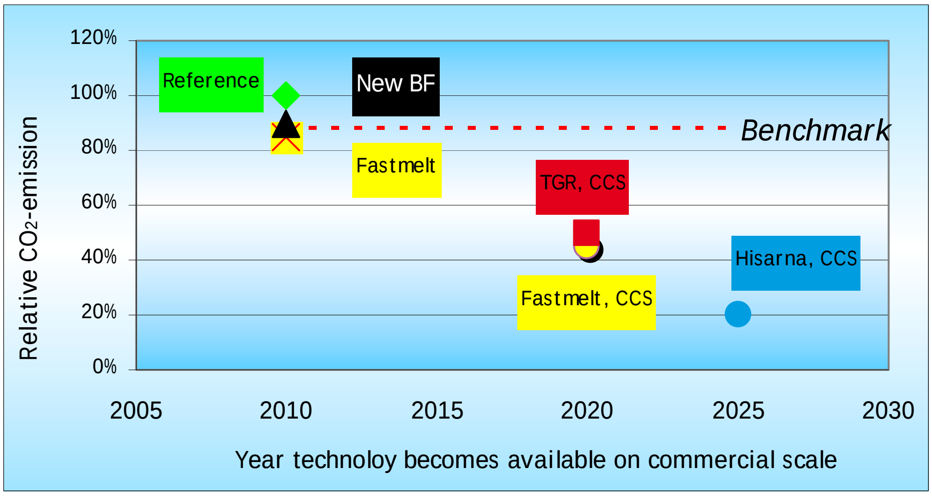
	Current EU average blast furnace	Blast furnace TGR configuration
Production capacity (Mtonne HM/year)	0.5-5.0	0.5-5.0
Energy consumption	100% (± 17 GJ/tonne HM)	
CO_2 emission tonne/tonne HM - With CCS: - Without CCS:	 1,650 1,650	 790 (-52%) Not relevant
CAPEX[28] - Greenfield - Brownfield	 100% -	 105% 25%
OPEX (incl. energy, excl. depreciation costs)	100%	120%

Sources: Link, 2008; Meijer, 2008.
Notes: The percentages should be interpreted as relative scores, as the performance of the reference average blast furnace is set at 100%. The other data are absolute figures.
HM = Hot metal (or pig-iron).

2.4 Selection of breakthrough technologies

Figure 11 presents the three technologies as dots that are expected to become available in the near future, indicating CO_2 reductions compared to the average European blast furnace (reference) that can be obtained and the timing of expected market introduction on the horizontal axis.

Figure 11 **Relative specific CO_2 emissions of steel production and time of implementation of considered technologies**



28 A greenfield site refers to a new industrial location without any infrastructure and other facilities and utilities. As a result investments for these issues have to be made too (so-called indirect investments). As reference a ± € 750 m/Mtonne production capacity is chosen. A brownfield site refers to an existing industrial site where these indirect investments have been made in the past.

Based on the available information on the technologies provided in Section 2.3, three breakthrough technologies can be identified:

1. The HIsarna process as the breakthrough technology being developed within the EU. It will require significantly lower capital investment costs (CAPEX) and will produce semi-finished products with the same quality as current breakthrough technology at significantly lower operational costs (OPEX), including reduced energy consumption. HIsarna will be capable of utilising a wider range of feedstocks and feedstocks of lower quality.
2. The fastmelt process is a relevant breakthrough technology being developed outside the EU. Its advantage is mainly its capability of utilising a wider range of feedstocks and feedstocks of lower quality. This significantly reduces OPEX (ex-depreciation costs) It will also produce semi-finished products that have the same quality as current breakthrough technology. The main drawbacks are the high CAPEX and the relatively large footprint. Energy consumption is slightly lower compared with current average EU level at blast furnaces. CO_2 emissions per tonne of hot metal are similar.
3. Top Gas Recycling since it will allow for a significant reduction in both CO_2 emissions and reducing agent consumption at new or existing blast furnaces. It is an optimisation of the existing blast furnace technology for the realisation of CCS in pig-iron production. TGR configuration is considered as a reference for newly built plants.

This approach is in line with the strategy in the ULCOS programme in which both HIsarna and TGR are being further developed. Within the ULCOS programme a broad perspective is taken, instead of focusing on one route. Expectations differ on which route might ultimately turn out to be the most promising. For example, some doubt exists as to whether HIsarna can be developed into a commercially mature technology as it is a new and – is perceived as – a more complex technology, compared to blast furnace which has been the main conversion process within iron and steel industry for ages. However, the HIsarna technology is based on a combination of technologies which have been proven (Hismelt plant in Australia and CCF demonstration plant). Also the technology resembles the Outokumpu flash smelting conversion technology applied in the non-ferrous metal industry for decades.

2.5 Potential breakthrough technologies

Both the HIsarna and Top Gas Recycling technologies require combination with CCS to achieve significant reductions in CO_2 emissions. This also is true for the Fastmelt technology. Given that perpetuate storage has not been demonstrated, the diversity of public opinion about deep geological CO_2 storage and given the potentially limited capacity of sufficiently safe geological reservoirs, this dependency is a drawback of the considered technologies.

As indicated in Section 2.3 there are at least three potential alternative carbon extensive technologies that are being developed at a slower pace within the technology programmes we considered:

- Natural gas and hydrogen based direct reduction processes with EAF.
- Biomass application.
- Electrolysis.

2.5.1 Natural gas and hydrogen

The first route of using natural gas and hydrogen based direct reduction processes with EAF is of little relevance for EU based steel production:

- At the moment, natural gas and hydrogen based processes are already on the market (see for example the Midrex, HyL, Circored, Finmet processes). The ULCOS II efforts are primarily aimed at optimising the natural gas based process, not at developing the concept of the process. The fact that natural gas based installations have been realised in countries such as Venezuela, Trinidad and Tobago and the different Gulf States in the Middle East, however, illustrates that these processes are economically viable only if cheap and stranded gas is available. The EU – where natural gas commodity market prices rage from € 6/GJ to € 8/GJ – is a less compatible place for such an installation.
- Another reason why direct reduction with natural gas is less relevant for this study – as already mentioned in Section 2.1 - is that since the ore is not melted and no slag is produced in direct reduction processes, the majority of impurities (sulphur, gangue constituents) are still present in the produced sponge iron. In order to enhance EAF steel quality the ore must contain low grades of impurities (< 5% weight), which, in practice, results in the restricted applicability of this kind of processes.
- Thirdly, even though natural gas gives an approximately 50% lower carbon emission per GJ, natural gas based processes still do not yield the CO_2 emission reduction required to stabilise atmospheric CO_2 concentration at 450 ppmv.

2.5.2 Biomass

A second measure - not requiring a change in the basic concept of the process - for reducing CO_2 emissions would be use of biomass as a reducing agent instead of fossil fuels.

Biomass can be considered carbon that is already present in the biosphere, temporarily assimilated in the shape of vegetation. As a consequence, use of biomass does not theoretically result in a change in atmospheric carbon concentration[29]. This is true only if the biomass is produced from cultivated not natural vegetation[30], e.g. agricultural crops and forested trees. Fossil fuels, on the other hand, can be considered as carbon presently stored in deep geological layers. Their use results in bringing back into circulation this geologically stored carbon, thereby increasing atmospheric CO_2 emissions.

A question that arises in using biomass is whether it can be considered sustainable. Criteria that can be used (see e.g. RED and NTA 8080) in that regard are:

- Making biomass available does not result in damage to the environment in the shape of, for example, deforestation, air and water pollution and reduction of biodiversity.
- The use of biomass is not associated with undesirable social and economic impact such as increases in food prices and expulsion of indigenous people from their land.

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[29] In practice, the avoidance is not 100% because of fossil fuel consumption in biofuels production and feedstock cultivation (e.g. fertiliser, diesel for machinery, heat). The avoidance is decelerated in time since the use of the biofuel instantly generates CO_2 which is only reassimilated as vegetation in the second instance.

[30] Natural vegetation and organic matter in soils, on the other hand, are effectively stocks of stored carbon as these pools will not (or only slightly) change in size overtime as long as they are not disturbed. A forest remains a forest with a constant standing stock of biomass, i.e., trees and undergrowth. Thus any reduction in the size of these stocks effectively boils down to creating net greenhouse gas emissions.

The amount of sustainable biomass available globally and in the EU at economically competitive prices is, however, limited:

- Globally to 50–100 EJ/year (Dornburg (2008), WBTU (2009)).
- In the EU to approximately 10–15 EJ/year (EEA, 2006).

Subsequently, there will be competition for the available sustainable biomass from other sectors (power sector, transports sector and other industrial sectors).

For comparison the demand for fuel and reducing agents in the EU steel, cement and pulp production, the sectors considered in this report, amounts to approximately 6.0 EJ/year (see EEA UNFCCC report). The demand in 2020 for sustainable biomass from the transport and energy sectors is estimated at another 6.5 EJ/year. This demand is likely to increase in the period beyond 2020 as indicated by the target for biofuels for 2030 currently under discussion.

Finally, it should be mentioned that not every type of biomass is suitable for use as a fuel or reducing agent in industrial processes. The preferred or probably the only applicable type of biomass is clean wood with low ash content or derived products such as charcoal. Clean wood is also the preferred fuel for biomass based power and heat generation. Since the available potential of this type of biomass is far smaller than the amounts mentioned above, significant sectoral competition could be expected if all sectors aimed at using large amounts of wood.

2.5.3 Electrolysis

In electrolysis the iron-ore is reduced by addition of electrons to iron supplied by electricity. This theoretically allows for complete carbon-neutral steel production – if the applied electricity can be produced without generating CO_2 emissions. However, although the principle of the process has been proven, the technology is still in the early stages of development and – according to the ULCOS II programme – requires another 20 years or more of development before the first commercial scale production facility could become operational. There is still a lot of basic research that has to be conducted to get a better understanding of the process. Moreover, sites where cheap and large potential of carbon-neutral electricity is available are limited – situated primarily in Norway and Iceland. Reduction of production costs of other carbon-neutral electricity production technologies just like the electrolysis technology require much additional technical development[31] before this production route becomes economically viable. In short, electrolysis seems more a technology for the longer-term.

On the other hand, given the possibilities for very significant CO_2 emission reduction without the need to combine it with CCS (as required for HIsarna and Fastmelt technologies), electrolysis would seem the preferred technology for enhancing sustainable development in the steel sector. This may be an argument for extra incentive to develop this technology.

[31] In (PBL, 2010) for example it is estimated that production costs for wind power could decline to values of € 50-60 per MWhe. However, these lower production costs are expected to be reached from 2035 on.

2.6 Summary of results

Table 6 summarises the environmental and economic performance of the breakthrough technologies and TGR. Recall that the current technology is a conventional blast furnace, whereas a new plant is standard expected to be one with TGR configuration.

Table 6 Overview of performance of innovative processes and current technology for pig-iron production

	Current EU average blast furnace	Blast furnace TGR configuration	Coke-free steelmaking*	Fastmelt direct reduction*
Production capacity (Mtonne HM/year)	0.5-5.0	0.5-5.0	0.5-1.0	0.5-1.0
Environmental aspects				
Energy consumption	100% (± 17 GJ/tonne HM)		80%	95-85%
CO_2 emission tonne/tonne HM				
- With CCS:	1,650	790 (-52%)	330 (-80%)	760 (?) (-54%)
- Without CCS:	1,650	Not relevant	1,320 (-20%)	1,590-1,420 (-5%)
Economic aspects				
CAPEX[32]				
- Greenfield	100%	105%	75%	200% - no CCS
- Brownfield	-	25%	65%	(?)
OPEX (incl. energy, excl. depreciation costs)	100%	120%	90%	80-90% (?) – no CCS

Sources: Link, 2008; Meijer, 2008, HIsarna description.

Notes: The percentages should be interpreted as relative scores, as the performance of the reference average cement kiln is set at 100%. The other data are absolute figures.

*= Identified as breakthrough technology, HM = hot metal (or pig-iron).

If we look at the currently proposed benchmark level for EU ETS allocation in phase 3, which is 1,460 kg CO_2 eq./tonne HM, we find that all the selected technologies score better. It turns out that the HIsarna process of coke-free steelmaking would offer the largest benefits compared to existing blast furnace technology with and without top gas recycling with respect to both energy consumption and greenhouse gas emissions. It also seems more attractive than any other option with respect to production costs; it can utilise a wider range of ores and coal qualities and is significantly more energy efficient than the current technology and comparable to other innovative processes. A potential problem arises with respect to societal acceptance of CCS.

[32] A greenfield site refers to a new industrial location without any infrastructure and other facilities and utilities. As a result investments for these issues have to be made too (so-called indirect investments). As reference a ± € 750 m/Mtonne production capacity is chosen. A brownfield site refers to an existing industrial site where these indirect investments have been made in the past.

In the longer-term, electrolyses might become a breakthrough technology allowing complete coverage of the intrinsic process of energy consumption by electricity from renewable sources. It might be able to achieve the required 80-95% CO_2 reduction. As mentioned, however, this option is not under development at the moment and not all aspects can be evaluated yet.

Please note that in the case of the Fastmelt process no study has been found that specifies the reduction in CO_2 emissions achievable by applying CCS in combination with this technology. The only indication found was in a technical paper produced by Corus Research indicating that for a rotary hearth furnace with associated EAF, the possibilities for CCS are limited. For OPEX, too, the estimate is based on a limited amount of information.

3 Cement sector

This chapter considers innovation in the cement sector. A brief introduction to the sector is provided in Section 3.1, covering some basic information on the cement market, products and production process. Section 3.2 describes CO_2 emissions and energy consumption, after which Section 3.3 goes into the current technical developments. The breakthrough technology for the cement sector as well as fall-back options are then identified in Section 3.4. Finally, Section 3.5 gives an overview of the findings. The economic and environmental performance of the evaluated technologies are summarised and a table lists the main characteristics of the breakthrough and fall-back technologies showing their main strengths and weaknesses.

3.1 Introduction to the sector

3.1.1 Market outline

The global cement market produced 2.55 billon tonnes in 2006 (IEA and WBCSD, 2009). China is the main player, accounting for approximately 50% of world production, followed at some distance by the EU with 10%. In the EU-27 region, total tonnage produced amounted to just over 267.1 million tonnes in 2006 at a value of € 19 billion. Output in 2007 is estimated to have reached 272 million tonnes. This represented approximately 0.5% of total value added and 0.25% of total employment in manufacturing. Demand for cement is cyclical, depending entirely on building and infrastructure requirements. Employment has been decreasing steadily over recent years, and in 2006, it is estimated that there were 56,500 direct jobs (EU-27).

Cement is produced in virtually all countries. It is an important construction material while the raw material (limestone) needed for cement production is geographically abundant (IEA, 2005). Yet, the top five EU producers have a 30% share in the global cement market (McKinsey, 2006) and most kilns are owned by a group of seven multinationals (Ponssard and Walker, 2008). Where European cement producers have identified demand for cement in non-EU countries, they have generally invested in manufacturing sites in those countries. As such, EU companies now own almost 60% of US production capacity, and have significant production facilities in the rest of the world.

There is limited international trade in cement[33]. Trade intensities between Europe and non-EU regions are about 7% there. This is mainly due to high transport costs, since cement is a heavyweight, homogeneous product that sells at a relatively low price. The cement industry is capital-intensive, with the cost of laying down a cement production installation equivalent to around three years' turnover (EC, 2010b)[34]. It is energy-intensive, with energy costs accounting for over a third of total production costs and entails very long-term investments.

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[33] Yet, in areas close to seaports and near (southern) EU borders, such as Greece, Italy, southern France and Spain, producers might face more international competition (Climate Strategies, 2007; NERI et al., 2007).

[34] Although compared to other heavy industry sectors - e.g. steel, refineries, power – capital intensity is not that high (Holcim, 2010).

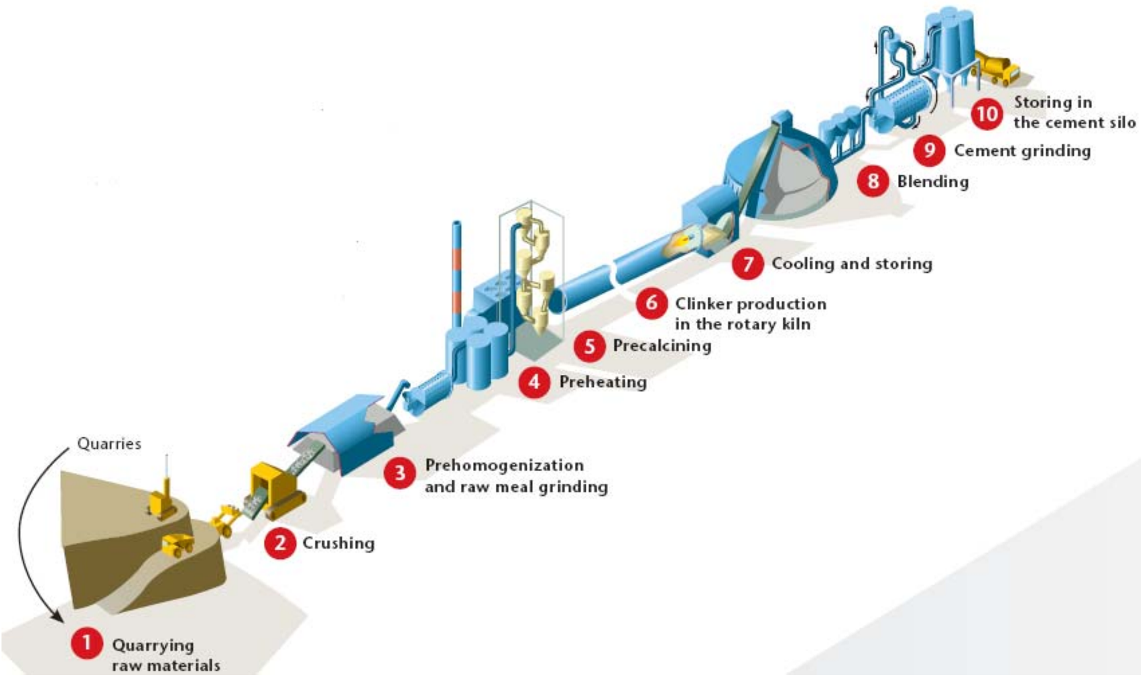
3.1.2 Production process

Cement as currently supplied to the market is a mixture of Portland clinker mixed with a varying percentage of 'substitutes' such as blast furnace slag or coal-fired power plant fly ash. The percentage of Portland clinker may be as high as 95% or as low as 50%.

For Portland clinker three types of production methods can be distinguished: dry, semi-dry and wet processes. In the EU-25, dry production process represents 95% of the total production, with only 5% accounted for by wet processes (McKinsey, 2006).

In cement production finely ground limestone and other raw materials are introduced to preheaters in which they are preheated by countercurrent flue gases. In modern kilns the preheated limestone is next calcinated (decomposing in lime and CO_2) in a separately fired pre-calciner after which the produced lime and other raw materials are burned into clinker in the kiln.

Figure 12 Flow sheet of cement production



Source: Schabrun, 2002.

Cement production boils down to cooling and finely grinding the clinker, after which this so called 'Ordinary Portland cement' can be mixed with other cement components.

3.2 CO_2 emissions and energy consumption

Cement manufacturing in the EU is a highly energy-intensive activity. It emits approximately 180 Mtonnes of CO_2 annually, thereby accounting for 16% of total industrial EU emissions (see Table 2). It contributes about 3% of the total anthropogenic emissions of energy related CO_2 in the EU and about 5% of the global anthropogenic emissions CO_2 (WBCSD, 2009).

The specific emissions for clinker production amount to approximately 840 kg CO_2 eq./tonne clinker[35]. The CO_2 emission consists of 40% energy related emissions and 60% process related emissions, caused by decarbonisation of the consumed lime stone raw material (calcinations). There are no other significant direct CO_2 emissions in cement production, as preparation of other cement raw materials such as blast furnace slag do not require large quantaties of fuel.

The specific heat consumption for the European cement industry is estimated in 2006 at 3,700 MJ/tonne clinker (Ecofys, 2008) – 2,800 MJ/tonne cement (at 75% clinker content (WBCSD, 2009)). The consumed electricity amounts on average to 100-110 kWh/tonne cement (in OECD Europe).The best performing plants – dry kilns with 6-stage pre-heater cyclone and pre-calciner – consume approximately 2,950 MJ/tonne clinker – 2,200 MJ/tonne cement (at 75% clinker content).

The Portland technology currently applied has reached a level of performance which for many individual plants cannot be improved upon with current technologies, so that further major improvements at the production stage are unlikely in the short term (EC, 2009b). In line with this, the proposed benchmark for clinker production is 780 kg CO_2/tonne clinker. This emission level is comparable with the emission of a cement kiln with a fuel consumption of approximately 2,950 MJ/tonne clinker – 2,200 MJ/tonne cement (at 75% clinker content).

Further energy optimisation seems possible by utilising the waste heat in the flue gases. In plants with maximum process heat integration (the 6-stage preheater precalciner dry kiln) flue gases still have a temperature of 2802ºC, high enough for applications such as:
- Hot water production for space heating or process steam generation.
- Electricity production with an ORC (see, for example,Werk Lengfurt (GER)and Heidelberger Zement AG; BLU, 2001).

An alternative measure that could be implemented immediately is a fuel switch to natural gas and biomass. With a combination of maximum biomass utilisation and natural gas to cover the remaining fuel demand, the CO_2 emission could theoretically be reduced to 570 kg per tonne clinker (assuming a 2,950 MJ/tonne clinker fuel demand)[36].

3.3 Current technological development

The main source of emissions in the cement sector is related to clinker production. Therefore, most efforts to realise abatement of CO_2 emissions are related to this part of the cement production. For a significant reduction of CO_2 emissions related to cement and clinker production four routes seem possible in theory:
- Combination of current technology with CCS.
- Combination of a high percentage of biomass cofiring.
- Substitution of clinker by other siliceous or silico-aluminous raw materials.
- Substitution of clinker by other strength developing anorganic polymers.

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[35] Cement production was 270 Mtonnes, 75% of which was clinker. Specific emission calculated as 180 ÷ (75% x 270) = 0,88.

[36] The emission of 570 kg/tonne clinker refers to the emission caused by decarbonisation of the limestone (CaCO3) raw material into CaO and the emitted CO_2.

With respect to R&D in this regard, a clear distinction can be made between the technical routes that are generally developed within the cement industry worldwide and options investigated by individual parties.

Industry-wide research into further reduction of CO_2 emissions, in programmes such as the Cement Sustainability Initiative (CSI)[37], focuses mainly on CCS in combination with oxyfuel combustion and on fuels with lower carbon intensity, primarily biomass. Development of Portland clinker substitutes is considered as a third path.

In addition, alternatives for Portland clinker based on other inorganic elements than calcium, silica and aluminium are actively being developed by small companies, such as Novacem in the EU, Calera in the USA and TechEco in Australia. Both Novacem and TechEco are developing magnesium based cements.

The three identified technologies are described below in more detail:
- Low carbon fuels like biomass or natural gas.
- Portland clinker substitutes.
- Oxyfuel and CCS.

After a short introduction on the stage of development and applied technology, we look at the strengths and weaknesses. Based on the available information, we have estimated production capacity and extracted the relative energy consumption volumes, CO_2 emissions and economic parameters for each technology compared to the reference technology (see Section 1.5.3).

The provided figures will focus on the clinker production since it is the main source of CO_2 emissions within the cement production process. Subsequently most technologies focus on reducing emissions that occur during this phase. Besides, four of the five processes considered produce 100% Portland clinker, so that this seems the most convenient and logical basis for comparison. Provided that the average cement in Europe currently consists for 75% of clinker, energy consumption and CO_2 emissions for EU average cement can be calculated by multiplying the figures by 75%.

3.3.1 Low carbon fuels

Introduction
Utilisation of low carbon fuels is already part of current operational practices. In 2006 alternative fuels constituted 18% of fuel consumption in clinker production across Europe (Cemburau, 2009). In Germany, however, alternative fuels made up 55% of total fuel consumption and in some specific kilns (e.g. ENCI, Maastricht) alternative fuels make up more than 80% of the fuel mix.

Technology
Theoretically a kiln could be fired solely with a fuel mixture of biomass and natural gas.

Strengths and weaknesses
The use of low carbon fuels would be beneficial from an environmental perspective, see Table 7. Fuel and electricity consumption, as well as CO_2 emissions are lower compared to the average cement kiln in Europe. Operational costs are expected to be higher due to relatively higher costs for sustainable biomass and natual gas. Compared to a new EU cement kiln that

[37] This programme is accomodated by the cement industry.

will be more energy-efficient than older kilns, the only advantage of biomass/natural gas utilisation being the lower CO_2 emissions from the use of alternative fuels.

Table 7 **Environmental and economic performance of biomass and natural gas utilisation compared to the current average technology for clinker production**

	Current EU average cement kiln	New EU cement kiln	New kiln, biomass + natural gas
Production capacity (Mtonne clinker/annum)	2.0	2.0	2.0
Fuel consumption	100% (= 3.7 GJ/tonne clinker)	80%	80%
Electricity consumption	100% (= 110 kWhe/tonne clinker)	80%	80%
CO_2 emission tonne/tonne clinker (with CCS)	0.88	0.79 (-10%)	0.57 (-35%)
CAPEX (greenfield, M€)	Not relevant	260	260
OPEX (incl. energy, excl. depreciation costs)	100%	90%%	138%

Sources: WBCSD, 2009; Ecofys, 2009b.

Note: The percentages should be interpreted as relative scores, as the performance of the reference average cement kiln is set at 100%. The other data are absolute figures.

Biomass firing as a CO_2 emission reduction measure only reduces fuel related emissions (40% of total clinker production is related CO_2 emissions). It does not impact raw material emissions. In addition, replacing all fossil fuels by biomass is not a realistic option either. First of all, the utilisation of biomass is limited by the required flame temperature in the main burner, which necessitates a fuel mixture with an average LHV of 20–22 MJ/kg. Possible maximum biomass share in fuel batch is estimated at (WBC technology road map papers) 75% for pre-calciner kilns and 40% for kilns without a pre-calciner.

Compared with current application rates there is still much potential for additional biomass firing on average within the EU. In some member states, such as Germany and the Netherlands, the potential is limited because the potential has already been utilised to a large extent. Also, there may be a public debate concerning the sustainability of the biomass utilised, whereas the availability of sustainable biomass is expected to be limited (see Section 2.4.2). Thirdly, biomass and natural gas are significantly more expensive than coal.

3.3.2 Portland clinker substitutes

Introduction

The use of Portland clinker substitutes is already practice in Europe. In 2006, the EU clinker ÷ cement ratio was approximately 0.75, indicating that cement contained 20% alternatives for Portland clinker, such as coal fly ash, blast furnace slag, natural Pozzolanes, limestone. The EU uses one of the highest percentages of clinker substituting materials globally. In specific applications cements with a Portland clinker content as low as 5% can be applied (CEM III cement type).

If we look at the development in relative markets shares of the various types of cement, however, the possibilities of expanding the current average amount of substitution in Europe (20%) seem limited to approximately 35% of total (see also CSI/ECRA technology papers):

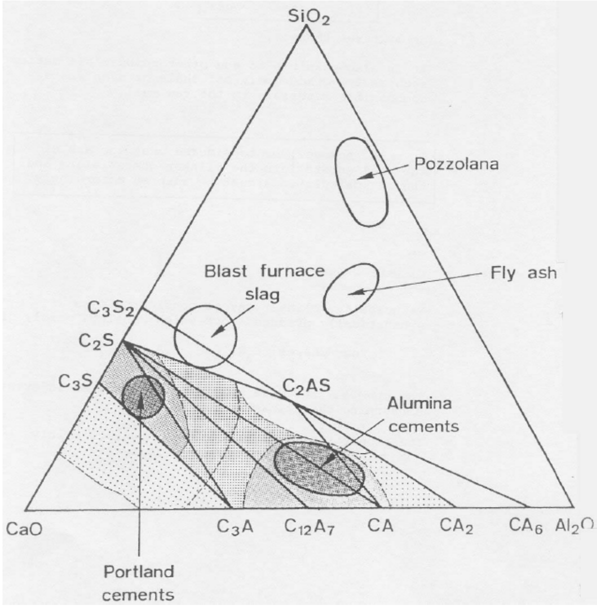
- In the period between 1994–2004 the percentage of Ordinary Portland Cement (95% clinker) was increasingly substituted by CEM II – Portland Composite (65-95% clinker).
- The share of cement types with a higher percentage of clinker substitutes (CEM III–CEM IV) hardly changed in this period.

This seems to indicate that low clinker cements serve a limited market and that the specific qualities offered by Portland clinker – resulting from its specific chemical composition (see Figure 13) - are required for the rest of the market. The potential of reducting CO_2 emissions of cement production by further substituting the Portland clinker content in cement is therefore limited to 10 to 20%.

Another drawback of most common substitutes is their limited availability. Current availability of blast furnace slag, coal power plant fly ash and natural pozzolanes is estimated at 800 Mtonne/annum, comparaed with a global cement consumption of 2,400 Mtonne/annum (WBC technology road map papers). The availability of some substitutes, such as fly ash from coal-fired power plants, may be further reduced when the energy sector becomes more sustainable. This does not apply to limestone, a raw material of Portland clinker. But limestone obviously does not have the same properties as a hydraulic binder like Portland clinker, being a raw material that must be processed at high temperatures.

That said, the above evaluation refers to the current state of technology, as described in e.g. WBCSD (2009). As indicated by for example Holcim, other alternatives are under development and could influence the given description. Due to a lack of more specific information, there was no opportunity to take these possible developments into account.

Figure 13 Illustration of the different chemical composition of Portland clinker and substitutes



Source: Lorea, 2006.

The implementation of magnesium based clinker might not be hampered by the restrictions discussed above for alternative siliceous or silico-aluminous raw materials. Before the widespread 20th century use of Portland cement magnesium oxide and magnesium chloride based cements were widely used (Swanson, 2010). Examples of structures built with magnesium based cements such as The Great Wall of China, Stupas in India and timber-frame buildings in Europe illustrate the durability of this kind of cement.

Novacem is currently developing an MgO based potential breakthrough cement technology. The developments aim to deliver a cement which will:

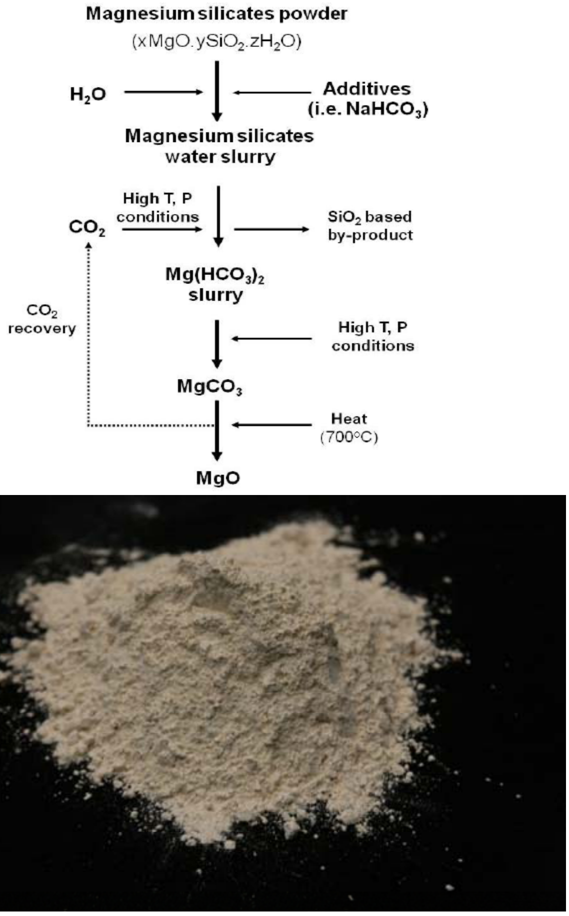
- Be as strong as Portland cement.
- Be as economic as Portland cement.
- Have a significant lower carbon footprint.
- Be based on raw materials available on a huge scale.

Magnesium based cements are offered as commercial products in the USA by, for example, The Bindan Company in Chicago and CeraTech.

Technology

In the production process of Novacem, conventional Portland clinker is substituted by magnesium based clinker. The product being developed by Novacem contains both magnesium oxide and magnesium carbonates (see Figure 14).

Figure 14 Illustration of the Novacem production process and produced magnesium oxide powder



Source: Novacem, 2010.

Novacem claims that the magnesium based clinker product has the advantage that the final product absorbs more CO_2 than is emitted during the production process, thereby creating a net CO_2 sink (see Table 8). The advantage is mainly due to:

1. The use of magnesium silicates whereby no CO_2 emissions are created by the raw material. By contrast for every tonne of ordinary Portland cement produced, 400 kg is of CO_2 is released from limestone. Novacem will leave limestone, with its stored CO_2 in the ground.
2. Production temperature requirements of just 700ºC, so low carbon content fuels, e.g., biomass, can be used more readily instead of fossil fuel energy which need to achieve temperatures of 1,450ºC.
3. The carbon negativity of the magnesium carbonates that could more than offset any emissions generated from other elements of the cement production.

Table 8 Comparison between net life cycle CO_2 emissions of Portland clinker and Novacem MgO based cement

	Production	Use	Net
Portland	0.88	-0.15	Average: 0.73
Novacem	0.1	-0.15	Average: -0.05

Strengths and weaknesses

Substitution of Portland clinker by Novacem magnesium based clinker would reduce both process related emissions and fuel related emissions or even create a CO_2 sink. Cost figures are similar to a new cement kiln based on current technology. Table 9 summarises the figures.

Table 9 Environmental and economic performance of Novacem compared to the current average technology for clinker production

	Current EU average cement kiln	New EU cement kiln	Magnesium based clinker*
Production capacity (Mtonne clinker/annum)	2.0	2.0	0.5–1.0
Fuel consumption	100% (= 3.7 GJ/tonne clinker)	80%	50%
Electricity consumption	100% (= 110 kWhe/tonne clinker)	80%	100-120%
CO_2 emission tonne/tonne clinker (with CCS)	0.88	0.79 (-10%)	-0.05 (?) (->100%)
CAPEX (greenfield, M€)	Not relevant	260	260 (?)
OPEX (incl. energy, excl. depreciation costs)	100%	90%%	100% (?)

Sources: WBCSD, 2009; Ecofys, 2009b; Novacem, 2010.

Note: The percentages should be interpreted as relative scores, as the performance of the reference average cement kiln is set at 100%. The other data are absolute figures.

Other benefits claimed by Novacem are:
- The cement is white, which allows it to be used for premium construction products.
- The cement can be recycled.

On the other hand, the produced cement still has to demonstrate performance and be accepted by the construction industry in the EU. It would be aided in achieving this by a shift from composition based standards to performance based standards for cement. The Novacem cement is intended firstly to be applied in non-load-bearing prefab concrete building parts. After it is proven in these applications its use will be extended to other applications.

In addition to product development, production technology needs to be developed. Novacem is already operating a pilot plant in London. The company has already cooperated on the development of this plant with Laing O'Rourke, one of the largest UK construction companies, with Rio Tinto, a global mining company, and with large engineering partners. It expects to open a semi-commercial plant in conjunction with industry partners in 2012. The output from this plant will be used to get the first applications to market. The first full-scale production plant will follow in 2015. Novacem aims to licence its technology on a non-exclusive basis to ensure widespread adoption.

3.3.3 CCS and oxyfuel

Introduction

A third alternative could be capture of the CO_2 produced from fuel and raw materials for perpetual deep geological storage. Both post-combustion and oxy-fuel capture technology could be applied according to WBCSD information. The WBCSD information suggests that the oxyfuel technology seems the most attractive option for new plants and has been considered in this study.

At the moment, there has been no experience with oxyfuel configurations of cement kilns in practice. A pilot plant might be planned in the near future since the option is currently being further developed by the European Cement Research Academy (ECRA). With development into a proven commercial scale technology expected to require at least 10 years, actual market deployment is only likely by about 2025. The exact timeline is, however, uncertain.

Technology

In oxyfuel firing the kiln is fired by combusting the fuel with pure oxygen instead of air. In order to limit flame temperature increases the oxygen is diluted with cooled and dedusted recirculated flue gases that consist primarily of CO_2 and water vapour. The flue gases are cleaned of SO_2 and NO_x, cooled and dried and – if required – further processed to reduce oxygen concentration. The cleaned CO_2 is compressed to super critical pressure for transportation and storage. Major technical issues being investigated are the reduction of air inleak in the system and the chemistry of the clinker production process.

Strengths and weaknesses

The use of oxyfuel combined with CCS is expected to reduce both process and fuel CO_2 emissions, as indicated by Table 10. Yet CCS will result in increased investments, increased operational costs and increased energy consumption. Also, the desirability of geological CO_2 storage is still the subject of fierce public debate.

Table 10 Environmental and economic performance of Oxyfuel cement compared to the current average technology for clinker production

	Current EU average cement kiln	New EU cement kiln	Oxyfuel cement kiln with CCS
Production capacity (Mtonne clinker/annum)	2.0	2.0	2.0
Fuel consumption	100% (= 3.7 GJ/tonne clinker)	80%	85%
Electricity consumption	100% (= 110 kWhe/tonne clinker)	80%	200%
CO_2 emission tonne/tonne clinker (with CCS)	0.88	0.79 (-10%)	0.1 (-89%)
CAPEX (greenfield, M€)	Not relevant	260	345
OPEX (incl. energy, excl. depreciation costs)	100%	90%%	133%

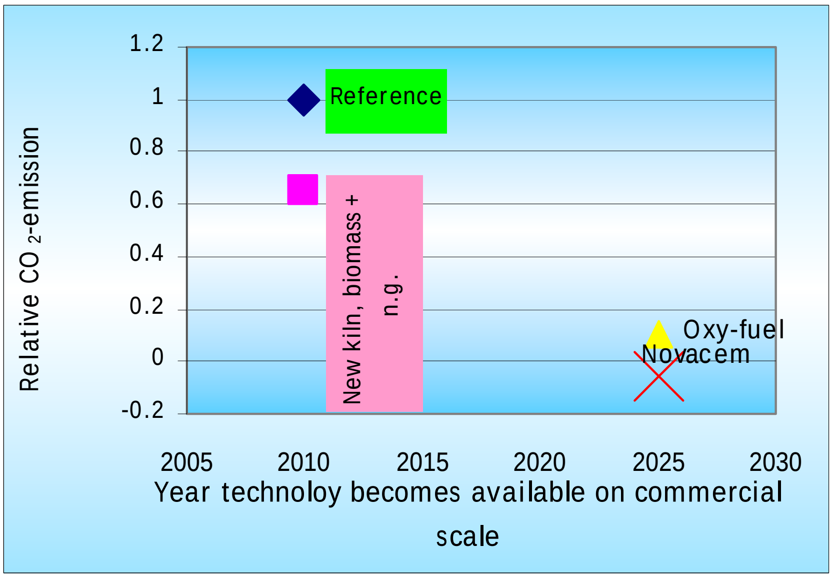
Sources: WBCSD, 2009; Ecofys, 2009b.

Notes: The percentages should be interpreted as relative scores, as the performance of the reference average cement kiln is set at 100%. The other data are absolute figures.

3.4 Selection of breakthrough technologies

Figure 15 shows the CO_2 reduction and timing of the expected market introduction of the three technologies referred to above. In addition, figures on the average European kiln (reference) and a new kiln based on conventional technology (new kiln) are included.

Figure 15 Relative specific CO_2 emissions of cement production and time of implementation of considered technologies



Based on publicly available information we have identified the Novacem cement system and the oxyfuel kiln with CCS as potential and future breakthrough technologies. If the Novacem technology can realise its announced aims, it will become a technology yielding a product of comparable quality at comparable cost but with a significantly lower specific CO_2 reduction (kg/tonne cement). Oxyfurel firing and CCS of captured CO_2 is a possible medium-term measure to realise significant CO_2 emission reduction, although operational costs are above average.

Back-up measures for CO_2 abatement in the cement sector would be:

- Increased use of biomass and natural gas, a directly implementable measure.
- Increased use of other siliceous or silico-aluminous raw materials as substitutes for Portland clinker, a directly implementable measure. However, the potential of this measure seems limited and may well decrease in time if coal based power production declines.

3.5 Potential breakthrough technologies

The evaluation has not indicated the existence of technologies are not further developed at the moment but that have the potential to become breakthrough technologies in the future[38]. The promising options for significant CO_2 reduction are already being developed within the cement sector. They are, accordingly, identified as breakthrough technologies.

3.6 Summary of results

Based on the available information, we have extracted the relative energy consumption volumes, CO_2 emissions and economic parameters for the breakthrough technology, the alternative (fall-back) options, the reference kiln and a newly-built kiln based on the conventional technology (see Section 1.5.3). Table 11 shows the results per unit of Portland or magnesium based clinker. As mentioned in Section 3.3, this seems the most convenient and logical basis for comparison. The reader can derive energy consumption and CO_2 emissions for EU average cement using a multiplication factor of 75%.

Table 11 Overview of performance of innovative processes and current technology for clinker production[39]

	Current EU average cement kiln	New EU cement kiln	New kiln, biomass +natural gas	Oxyfuel cement kiln with CCS	Novacem*
Production capacity (Mtonne clinker/annum)	2.0	2.0	2.0	2.0	0.5 – 1.0
Environmental aspects					
Fuel consumption	100% (= 3.7 GJ/tonne clinker)	80%	80%	85%	50%
Electricity consumption	100% (= 110 kWhe/tonne clinker)	80%	80%	200%	100-120%
CO_2 emission tonne/tonne clinker (with CCS)	0.88	0.79 (-10%)	0.57 (-35%)	0.1 (-89%)	-0.05 (?) (->100%)
Economic aspects					
CAPEX (greenfield, M€)	Not relevant	260	260	345	260 (?)
OPEX (incl. energy, excl. depreciation costs)	100%	90%%	138%	133%	100% (?)

Sources: WBCSD, 2009; Ecofys, 2009b; Novacem, 2010.

Notes: The percentages should be interpreted as relative scores, as the performance of the reference average cement kiln is set at 100%. The other data are absolute figures.

*= Identified as potential future breakthrough technology.

38 Except the potential development of additional alternatives to Portland clinker, on which we were not able to gather more specific information (see Section 3.3.2.)

39 Extra substitution of Portland clinker is not included here. The measures in the table have an impact on emissions during clinker production and thereby affect the CO_2 emissions of the final product. Reducing the share of Portland clinker in cement operates at a different level: CO_2 emissions per unit cement is reduced because less clinker is used.

If we look at the currently proposed benchmark for EU ETS allocation in phase 3, which is 780 kg CO_2 eq./tonne clinker (or 585 kg CO_2 eq./tonne cement at the current average clinker content in cement)[40] we find that all the selected technologies score better. Based on Table 11, we can further conclude that the Novacem process of using magnesium based clinker - if the technology can achieve its aims – would be the most desirable route for clinker production. It would become a technology yielding a product with comparable quality at costs comparable with current production but with a significantly lower specific CO_2 reduction (kg/tonne clinker). However, the Novacem technology is still immature and claims cannot be proven (yet).

Oxyfuel technology with CCS implemented at Portland clinker kilns is a technical alternative that captures both process emissions and fuel emissions. This technology path would have the benefit of producing a product familiar to the market. CAPEX and OPEX would, however, be higher than for current production.

40 As indicated in Section 3.3.2 the clinker content in cement can vary between 100 and 10% and shows a large variation within a certain class of cement too (e.g. from 95 to 65%).

4 Paper and pulp sector

This chapter considers innovation in the paper and pulp sector. A brief introduction to the sector is provided in Section 4.1, covering some basic information on the paper and pulp market, products and production process. Section 4.2 describes CO_2 emissions and energy consumption, after which Section 4.3 goes into the current technical developments and Section 4.4 looks at potential future alternative routes. The breakthrough technology is then identified in Section 4.5. This chapter concludes with an overview of the findings in Section 4.6. The economic and environmental performances of the evaluated technologies are summarised. In addition a table lists the main characteristics of the breakthrough technologies, showing their main strengths and weaknesses.

4.1 Introduction to the sector

4.1.1 Market outline

There is an international market for paper and pulp[41] in which Europe represents a quarter of world's paper production and consumption. Its paper industry produces 99 million tonnes of paper and board and more than 90 million tonnes of pulp per year (McKinsey, 2006; CEPI, 2009). This pulp production is almost equally split between production from recovered fibre, i.e. secondary pulp, and production from wood, the so-called primary pulp (McKinsey, 2006). The production of primary pulp is dominated by chemical pulping (30%), with smaller shares produced by mechanical (6%) and thermomechanical (12% of production) pulping.

According to the latest structural data available, there were in the total pulp and paper sector 756 firms employing 243,300 people in the sector in 2008, with turnover reaching € 78 billion. Wage-adjusted labour productivity (the relationship between apparent labour productivity and average personnel costs) was 145% and the gross operating rate (the share of operating surplus in turnover) was 9.9%. In 2006, "pulp manufacturing" represented 5% of added value and 2% of employment, "paper manufacturing" 39% and 29% and "articles of paper and paperboard" 56 and 69% respectively.

With rising pressure on primary raw materials, the use of recovered raw materials is on the increase. Today, about half of EU paper production is based on recovered paper, a growth of 25% since 1998. Paper recovery and recycling, linked to increased processing efficiency, have allowed a substantial production increase without the need to use more new wood.

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[41] In which paper faces competition from alternative markets such as plastics in the packaging sector and alternative media in communication (IEA, 2005a). The continuing development of electronic media has meant a reduction in certain paper based printing and publishing segments, such as newsprint.

As is the case for other forest based industries, the costs of energy and wood, which provides about half of the source of fibre for paper making, play a pivotal role in the pulp and paper sector. The overall costs for paper making break down as follows:
- Fibres 32%.
- Capital 18%.
- Personnel 14%.
- Energy 13%.
- Chemicals 12%.

The paper market is highly diversified with various possible applications of paper vary from printing paper to packaging. In some market segments most pulp and paper grades are commodities whose prices are set by the lowest-cost producers in the global markets. Non-EU competitors are said to have the advantage there that they do not have to bear the costs of compliance with European envirohnmental regulation. Nonetheless, the sector has a good opportunity for diversification and creation of added value in the shape of intelligent paper and packaging[42]. Increased management of both primary and secondary fibre supplies and their efficient use, including energy within the pulp, paper and converting industries and elsewhere offer further prospects for diversification.

The pulp manufacturing industry consists for the most part of large and very large firms, often multi-nationals, which are frequently involved with paper operations. They are very capital-intensive industries, as a new breakthrough pulp mill costs around € 1 billion, or even more if it is part of a paper mill. Paper mills for "commodity grades" of paper, i.e. those intended for further cutting into sheets or rolls or subsequent conversion into products, are most often also large or very large and also quite capital-intensive, especially if there are several paper machines on one site. Plants producing speciality grades may be smaller. Conversely, most converting mills, i.e. those producing usable paper products, are SMEs. Ranked by the CR10 index for concentration (i.e. market share of the ten biggest suppliers), concentration in the paper making subsector is as follows: high (> 85%) for coated mechanical paper, uncoated mechanical paper, newsprint and coated wood free paper; medium (65% to 85%) for cardboard, market pulp, and tissue paper; low (< 65%) for uncoated wood, free, container board and wrapping papers.

4.1.2 Production process

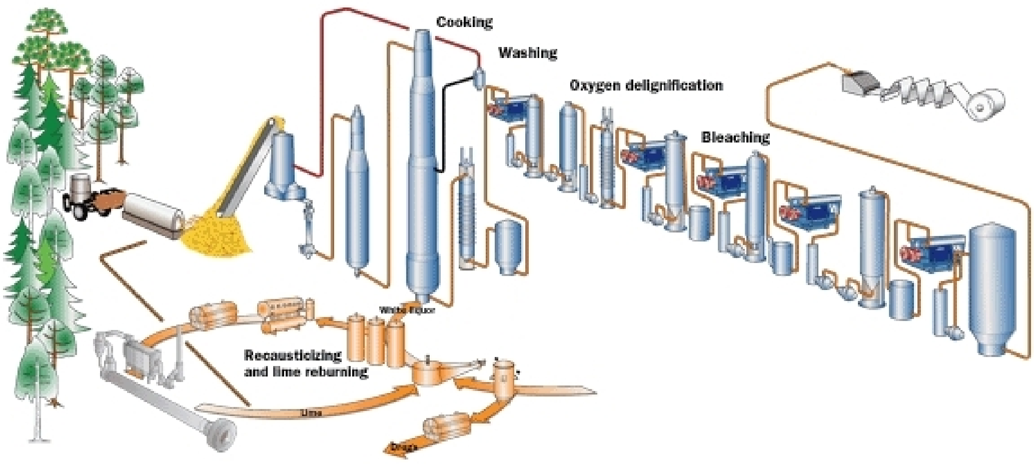
In the EU, pulp production is almost equally split between production from recovered fibre, i.e. secondary pulp, and production from wood fibres, the so-called primary pulp (McKinsey, 2006). Depending on the technology either all the fibres present in the wood or just the cellulosic fibres in the wood are isolated. Cellulosic pulp is required for paper that is sufficiently white, is thermally printable (e.g. copier paper) and which can be stored for a long time without losing whiteness and paper strength.

In the case of mechanical pulping, all wood fibres can be utilised – e.g. in newspapers – and the debarked wood is milled. A pre-treatment may be applied, e.g. softening the wood by applying heat. This process is called thermal mechanical pulping.

[42] The development of innovative and added-value products and systems, including "smart papers" and packaging, is expected to provide new market opportunities (EC, 2010)

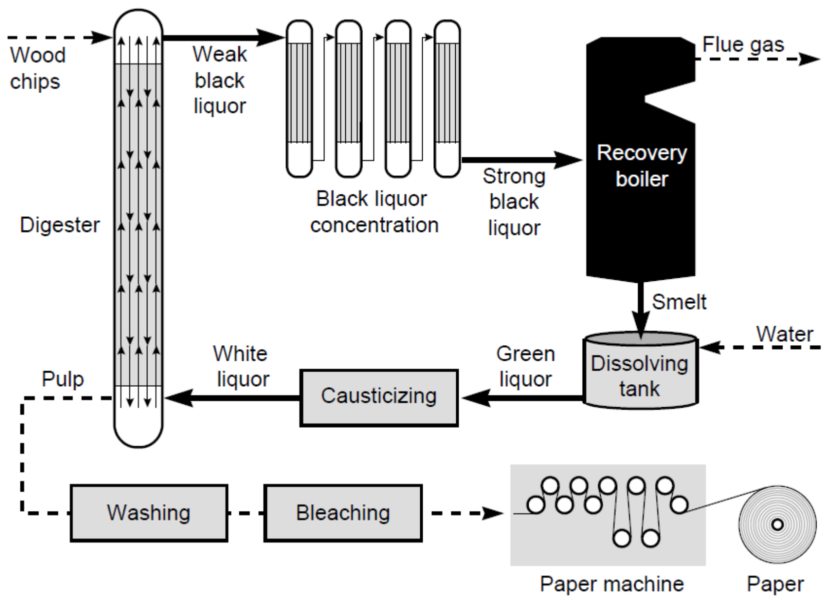
Cellulosic fibres are produced by cooking debarked wood in an alkali solution at increased pressure, thereby destroying the lignin and hemicellulosic polymers, which dissolve in the solution (chemical pulping)[43]. This is the most common primary pulp production process in Europe. Cellulosic fibres are isolated by screening. The lignin and hemicelluloses solution – green liquor - is concentrated by evaporation into a concentrate called black liquor which is subsequently burned in the so-called recovery boiler. Bark is burned in a separate boiler.

Figure 16 Illustration of chemical pulp production route



Source: www.wikipedia.org.

Figure 17 Flowsheet of chemical pulp production



Source: Ekbom, 2003.

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43 Wood can be regarded a mixture of cellulosic fibres, hemicellulosic fibres and branched lignin polymers. In chemical pulping the cellulosic fibre used in paper is isolated by destroying the other two wood components.

The produced primary fibres are next mixed with water to form a slurry. This is also the point in paper production where secondary raw materials (= separately collected waste paper) enter the production chain. The typical process for generating pulp from recovered paper feedstock involves blending the feedstock with hot water in a large tank. Pulping chemicals are sometimes added to the process to aid in the production of a fibrous slurry.

The slurry of primary and – if appropriate – secondary fibres is fed into the so-called wet end of the papermaking machine where a paper web (i.e., sheet) is formed. The slurry first enters a headbox, which creates a uniform layer of slurry and deposits this layer onto a moving fabric (also called wire or forming fabric). This fabric forms the fibres into a continuous web while allowing water removal via gravity and the application of vacuum pressure. Once the fibres have been sufficiently dewatered that they begin to bond to form paper, they move on to the press section of the paper machine. The dewatered sheet then proceeds to the so-called dry end of the paper machine for further drying and finishing operations. Dry-end processes include drying, calendering and reeling. In the drying section, steam heated rollers compress and further dry the sheet through evaporation.

Almost all mechanical pulp mills and the majority of chemical pulp mills are integrated with paper making (see Table 12). Part of the chemical pulp is produced in non-integrated plants and is sold commercially.
On the other hand, paper and board mills are not necessarily integrated with primary pulp production. There are numerous paper and board mills that process a mixture of in-house pulped waste paper/board and chemical pulp purchased from non-integrated chemical pulp mills.

Table 12 Overview of number of mills and level of integration in the EU pulp and paper industry

	Number of installations	Number of integrated installations (pulp + paper)
Dissolving pulp	4	1
Kraft pulp	84	56
Sulphite pulp	20	16
TMP/CMTP	20	14
Other mechanical pulp	64	59
Semi-mechanical pulp	10	9
Other pulps	7	4

Source: Ecofys, 2009.

4.2 CO_2 emissions and energy consumption

In 2007 the EU pulp and paper sector emitted 31 Mtonnes (Ecofys paper, 2009) to 41 Mtonnes CO_2 (CEPI, 2008), representing 4% of European industrial CO_2 emissions (see Table 2), 2% if public power emissions are included. A reason for differences between the CEPI and CITL data is the identification of combustion installations belonging to the sector and the fact that the UK installations under the climate change levy agreement were not included in the EU ETS in the first trading period, while being an important and significant paper sector and emitter.

Energy consumption per sub-sector and process

Indicative figures for energy demand are given in Table 13. Indications of benchmark energy consumption with current breakthrough technology are included.

Table 13 Indicative energy consumption figures for different processes in the paper and pulp sector

	EU Benchmark (Ecofys, 2009)			Modern mill other sources			Average EU		
	Steam	Fuel	kWhe	Steam	Fuel	kWhe	Steam	Fuel	kWhe
Pulp industry									
Kraft pulp, unbleached		0,86							
Kraft pulp, bleached	10	0,86		9 -12	1.2 – 1.5	640 - 660	10 - 14	1 - 2	640
Sulphite pulp	16	0,86							
Groundwood or mechanical pulping	0								1600-2200
Thermomechenical pulping	0							3	1500
Paper industry							± 8		670
Card board	6,7								550-700
Case Materials, corrugated board	6,0								
Wrappings and other packaging	7,0								850
Graphic paper	6,7								550-700
Newspaper	5,0								500-650
Tissues	7,0							5-25	1,000-3,000
Specialities	6,0								

Source: Ecofys, 2009; Caddet, 2001; Canada, 2002; BAT REF, 2001.

CO_2 emissions

For more insight in the breakthrough technology required for a significant reduction in the pulp and paper industry we produced a rough estimate of the fossil fuel use and decarbonisation related CO_2 emissions in this sector (see Table 14). The numbers are strictly indicative and do not represent actual amounts, but merely illustrate relative sizes of the different emission sources within the pulp and paper industry.

Table 14 **Indicative overview of CO_2 emissions in the pulp and paper sector**

	Production EU	CO_2 emissions			
	Mtonne/ annum	Residual Oil	Natural gas	CO_2/ton product	Mtonne/ annum
Pulp industry					
Kraft pulp, unbleached (fuel)	6	1.0	1	0.13	0.8
Kraft pulp, bleached (fuel)	19	1.0	1	0.13	2.5
Sulphite pulp (fuel)	2	1.0	1	0.13	0.3
Chemical pulps, carbonisation of limestone	28				5
Groundwood or mechanical pulping	5			0.0	0
Thermomechenical pulping	9		0	0.0	0
Paper industry					
Card board	8		6.7	0.4	3
Case Materials, corrugated board	24		5.9	0.3	8
Wrappings and other packaging	8		6.3	0.4	3
Graphic paper	37				
- Integrated plants	24				
- Not-integrated plants	13		6.7	0.4	5
Newspaper	11		5.1	0.3	3
Tissues	7		5.5	0.3	2
Specialities	4		6.0	0.3	1
Unaccounted fuel uses	99				9.0
					43.5

The total emission has been estimated based on the total fossil fuel consumption figures for 2008 given by CEPI. These have been multiplied by IPCC fossil fuels CO_2 emission factors.
Source: Production figures from CEPI, 2009, for energy consumption figures see text.

As indicated in Table 14 the CO_2 emissions associated with pulp and paper production are mainly related to natural gas consumption in pulp processing into board and paper. The production of paper and board semi-manufactured products requires significant amounts of fuel for the evaporation of the water applied in pulp slurry.

Mechanical pulping and thermomechanical pulping give (almost) no CO_2 emissions due to the limited fuel consumption in the processes. Though chemical pulping is the most energy-intensive activity within the pulp and paper sector, it is not the main source of CO_2 emissions. Chemical pulping fuel demand is largely covered by combustion of bark and degraded lignin and hemicellulose (see also Table 13). The amount of organic materials is more than sufficient for a modern mill to cover both the mill's own steam demand and power demand (see Table 15). In fact the CO_2 emissions due to decarbonisation of limestone at the lime kiln of the pulp mill is by far the largest source of long cyclic carbon in the mill. The lime kiln accounts for half (older mills) to all (newer mills) of the mill's fossil fuel consumption and for the decarbonisation emissions.

Table 15 **Fuel, steam and electricity balances for a modern Kraft pulp mill**

Mill type	Units	Non-integrated and bark sold	Non-integrated and bark fired	Fully integrated and bark fired
Heat generation				
Black liquor	GJ/annum	18	18	18
Bark	GJ/annum		4.2	4.2
	GJ/annum	18	22.2	22.2
Heat consumption				
Pulp mill process	GJ/annum	11.7	11.7	9
Paper mill process	GJ/annum			6.5
Back-pressure power	GJ/annum	3.2	3.2	4.4
Condesing power	GJ/annum	3.1	7.3	2.3
	GJ/annum	18	22.2	22.2
Power generation				
Back-pressure	kWhe/annum	870	870	1200
Condensing	kWhe/annum	300	710	225
	kWhe/annum	1,170	1,580	1,425
Power consumption				
Pulp mill process	kWhe/annum	660	700	550
Paper mill process		kWhe/annum		650
Excess sold	kWhe/annum	510	880	225
	kWhe/annum	1,170	1,580	1,425

Source: All figures from Caddet, 2001.

The figures given in Table 14 are indicative. For example, the assumed natural gas consumptions for semi-manufactured products are actually the benchmark energy consumptions proposed in (Ecofys, 2009). Still they paint a clear picture indicating that for realisation of a 90% reduction of greenhouse gas emissions in the pulp and paper sector, chemical pulp production must become a significant net sink and/or CO_2 emissions related to paper and board semi-manufactured products must be significantly reduced (see next section).

4.3 Current technological developments

In view of realisation of a significant reduction of greenhouse gas emissions in the pulp and paper sector, one route seems to offer good medium-term potential. In Sweden efforts are being made to develop black liquor gasification into a commercial technology. The effort is primarily aimed at production of biofuels. Gasification could however be combined with CCS to turn chemical pulp production into a significant net CO_2 sink. Additionally, one might try to significantly reduce CO_2 emissions related to paper and board semi manufactured products. This would be an option in the longer run (see Section 4.6).

4.3.1 Black liquor gasification and CCS

Introduction

The Swedish company Chemrec has developed a black liquor gasification process. One commercial scale installation of this technology has been operational for a decade in the New Bern pulp mill (see Figure 18). Chemrec is currently demonstrating production of DME – a biofuel – via black liquor gasification in a pilot plant at the Smurfit Kappa Pitea Kraft pulp mill, the largest Kraft pulp mill in Europe (Chemrec, 2009). The pilot plant gasifies 20 tonnes of black liquor per day. A second, large-scale demonstration plant is being built at the Domsjö pulp mill.

Technology

The conversion of black liquor into transport fuels would obviously extract a large part of the fuels required for the pulping process, which *might*[44] necessitate increased fossil fuel consumption in pulp production. The demonstration does, however, illustrate the possibilities of black liquor gasification and subsequent CO_2 capture. Part of the carbon present in the black liquor is rejected as CO_2 in the gas cleaning. This waste gas would pose a good opportunity for CCS demonstration. Gasification offers the opportunity of precombustion CO_2 capture: the capture of all carbon as CO_2 from the produced syngas before the syngas is burned.

Figure 18 Chemrec 50 MW black liquor gasification plant at New Bern pulp mill

Source: Chemrec, 2010.

44 According to the studies conducted by Ekbom which are mentioned.

Turning chemical pulp production into a net sink of carbon requires CCS of CO_2 of both fossil and biogenic origins. CCS could theoretically be applied on both recovery boiler, i.e., black liquor processing, and lime kiln. However, applying CCS at the lime kiln seems less attractive.
Applying CCS on the lime kiln is comparable to applying CCS on a cement kiln. The main difference is size. The lime kiln of a pulp mill is much smaller than a cement kiln. As a consequence, CCS at a pulp mill lime kiln will be (much) more expensive than CCS at a cement kiln. It is therefore considered a less realistic option. Theoretically an alternative could be production of lime in central large-scale lime kilns of a production size at which CCS is more realistic. However, this does not seem very realistic given the level of integration between lime kiln and cooking cycle at the paper mill.

Strengths and weaknesses

The amount of carbon in the fuel present in the black liquor is comparable[45] to the amount of carbon present in the produced pulp (± 12.6 Mtonnes/year[46]). Capture of 90% (a common capture rate) of the carbon present in the black liquor would mean removal of approximately 40 Mtonnes/year of CO_2, an amount comparable with the current fossil fuel consumption and decarbonisation related CO_2 emission of the entire pulp and paper industry. It would indeed be an option that would significantly reduce the CO_2 emissions of the combined pulp and paper industry.

For CCS of the carbon present in black liquor technological developments are going in the required direction. Investements costs are, however, higher than the current average in Europe. This is probably true for operational costs, too. Table 16 summarises the results.

45 The assumption that the amounts of carbon in pulp and black liquor are comparable is based on the fact that approximately 50% of the debarked wood is isolated as pulp. The wood components dissolved in the green liquor and concentrated in the black liquor amount to approximately 40% of the processed wood. Cellulose contains 45% carbon, while the dissolved lignin and hemicellulose contain 45 and 55% carbon respectively. The lignin is the bulk of the dissolved organic compounds. Comparing both amounts: 45% x 50% ÷ 40% x 50% ≈ 1 ÷ 1.

46 Chemical pulp production amounts to approximately 28 Mtonnes annually. Assuming the same composition as cellulose the pulp would contain 28 x 45% = 12.6 Mtonnes of carbon.

Table 16 **Environmental and economic performance of Chemrec compared to the current average technology for pulp production**

	Current EU average Kraft pulp mill	Kraft pulp mill with Chemrec*
Production capacity (Mtonne pulp/annum)	0.8	0.8
Steam	100% (= 12 GJ/tonne pulp)	100%
Electricity	100% (= 680 kWhe/tonne pulp)	125% (?)
CO_2 emission tonne/tonne pulp (with CCS)	0.18	-1.4 (->100%)
CAPEX black liquor processing M€ (brownfield)	170	± 345
OPEX (depreciation costs excluded)	100%	> 100% To be estimated

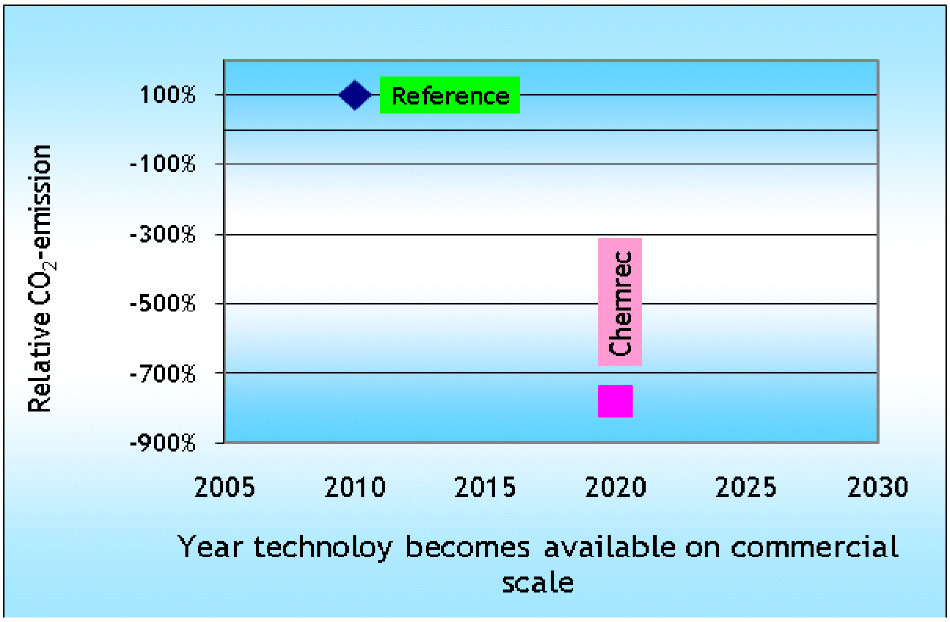
Sources: Ekstrom, 2005.

Notes: The percentages should be interpreted as relative scores, as the performance of the reference average cement kiln is set at 100%. The other data are absolute figures.

4.4 Selection of Breakthrough technologies

It seems that for significant CO_2 reductions in the pulp and paper industry there is only one technology requiring limited additional development that could be implemented in a relatively short term: black liquor gasification with subsequent capture of CO_2. This process may change chemical pulp production into a carbon sink by capturing CO_2 from black liquor for geological storage.

Figure 19 **Relative specific CO_2 emissions of paper production and time of implementation of considered technologies**



The percentages refer to the average specific CO_2 emissions of the Kraft pulp process (± 130 kg/tonne pulp, see Table 14).

For the true source of the fossil fuel derived CO_2 emissions, paper production and drying, no innovative technology seems to be under development. In the future innovation in paper drying technologies are worth looking at.

4.5 Potential breakthrough technologies

To realise a significant reduction of energy consumption in paper and board semi-manufactured production, only drying processes that reutilise the heat of vaporisation of the removed water allow for a significant reduction in fuel consumption. The most notable examples of such technologies are airless drying and superheated steam drying. Calims have been made for both processes concerning the potential of reducing fuel consumption by 70-90% compared to conventional drying[47]. Other innovative drying technologies in the wet end or dry end of the paper machine realise savings of 10-20% in fuel requirement (Condebelt, air or steam impingement drying) or can be applied only for some types of semi-manufactured goods (shoe press).

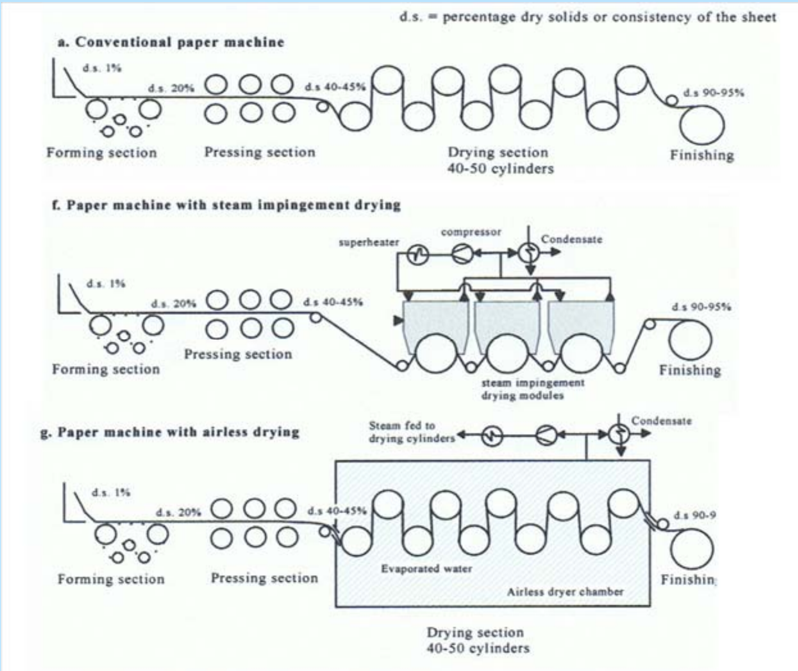
Airless drying and super heated steam drying

Airless drying

The airless drying technology is based on mechanical vapour recompression and comes down to compression of the evaporating water from the paper sheet to 4 bars. The water vapour subsequently condenses. The released condensation heat is utilised to dry the paper sheet. Vapour compression causes the electricity consumption of the paper mill to increase by 15%. Additional investments are estimated in (Alsema, 2001) at € 25/GJ of heat supplied to the drying process.

Superheated steam drying

In superheated steam drying the temperature of the steam is maintained at a high enough level for the steam not to condense during the drying process, while at the same time heating the moisture in the paper to temperatures at which the water can be applied as steam.



47 For airless drying see VNP, 2003; Alsema, 2001, all based on De Beer, 1998, for superheated steam drying see Deventer, 2004.

Though portrayed as a very promising technology in several studies, no recent information about applications in paper production have been found in more recent international studies or on the World Wide Web. This probably indicates that development as a paper drying technology have ceased or have never been adopted. This suggests little probability that such a breakthrough technology with its significantly reduced fuel consumption can be implemented in the paper industry on a large-scale within the next one or two decades. On the other hand, both technologies have found ample applications in other sectors, primarily for batchdrying.

4.6 Summary of results

Based on available information, we have extracted the relative energy consumption volumes, CO_2 emissions and economic parameters for the breakthrough technology and the reference technology. Table 17 provides the results.

Table 17 Overview of performance of the innovative process and current technology for pulp production

	Current EU average Kraft pulp mill	Kraft pulp mill with Chemrec*
Production capacity (Mtonne pulp/annum)	0.8	0.8
Environmental aspects		
Steam	100% (= 12 GJ/tonne pulp)	100%
Electricity	100% (= 680 kWhe/tonne pulp)	125% (?)
CO_2 emission tonne/tonne pulp (with CCS)	0.18	-1.4 (->100%)
Economic aspects		
CAPEX black liquor processing M€ (brownfield)	170	± 345
OPEX (depreciation costs excluded)	100%	> 100% To be estimated
Labour intensity	100%	≅ 100% (?)

Sources: Ekstrom, 2005.

Notes: The percentages should be interpreted as relative scores, as the performance of the reference average cement kiln is set at 100%. The other data are absolute figures.

*= Identified as breakthrough technology.

At a pulp mill where the black liquor recovery boiler needs rebuilding, the boiler could also be substituted by a gasifier with subsequent gas cleaning, shift reactor for conversion of CO into CO_2 and a CO_2 capture process. The remaining hydrogen rich gas would be burned in a boiler for the production of the steam required for the pulping process. Electricity could be produced by combusting part of the remaining syngas in a gas turbine with a heat recovery boiler. In both cases it may be diluted to minimise the NO_x emission. Both applications of hydrogen rich gas have been proven at oil refineries.

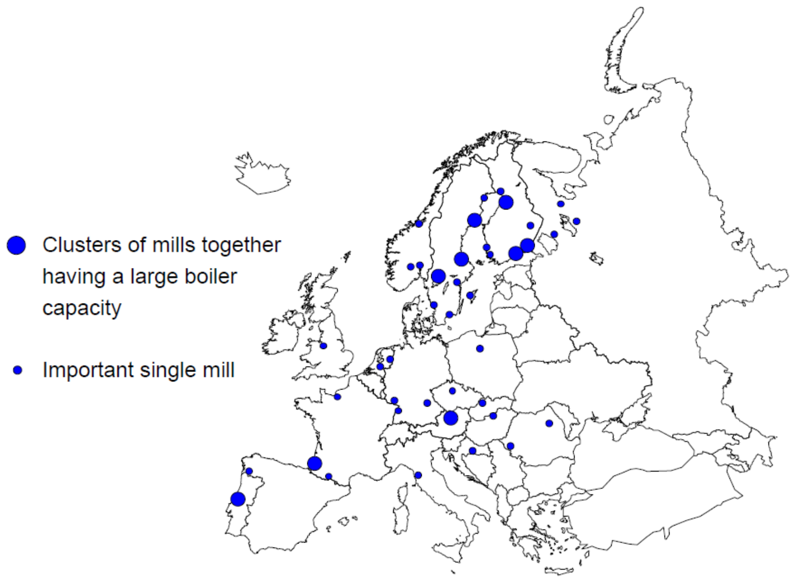
Investment estimates made in the Alterner BLGMF II study for a standardised pulp plant with a production of 2,000 tonne/day indicate that a black liquor gasifier with a subsequent methanol production unit requires an investment that is approximately twice that of a recovery boiler – € 345 m instead of € 171 m. In the methanol case considered in (Ekbom, 2005) part of the carbon already present in the black liquor is captured as CO_2. A comparable investment can be expected fFor a case in which as much CO_2 as possible is captured, dried and compressed for transportation to the storage location. Though there is no need for a methanol plant, extra components are required, e.g. a compressor for CO_2 compression.

The plant would allow capture of approximately 1.2 Mtonne/year of CO_2. Our first estimate based on the information in Ekbom (2005) and on Larson (2007) would be that supercritical CO_2 ready for deep geological storage could be captured at a cost in the range of € 10-20 per tonne. The added benefit of a gasification system would be a significant reduction in emissions of SO_2 and PM (see BAT REF paper).
As far as technical maturity is concerned, it appears that the black liquor gasification process itself is the least developed part. Syngas treatment, shift of CO and CO_2 capture from syngas are all technologies applied in numerous industrial processes and oil and coal gasification processes around the world.

A drawback of the considered technology route is that most Scandinavian pulp mills are far from the regions where a CO_2 transportation infrastructure is expected to develop: Western Europe (see Figure 20). However, CO_2 could also be transported by ship. This will certainly add to the costs, but is technically feasible. Worldwide four ships are used for the transport of liquefied food-grade CO_2 from large point sources of concentrated CO_2 such as ammonia plants in northern Europe to coastal distribution terminals in the consuming regions (IPCC (2005).

As with the other technologies considered in this report public acceptance of CCS is an important precondition for implementation of this technology. And, as stated before, there is still no experience with perpetual deep geological storage of CO_2.

Figure 20 Regional distribution of pulp mills in the EU



Source: Ekbom, 2003.

5 Conclusions

This chapter summarises the research findings and makes policy recommendations. Section 5.1 provides an overview of technologies that are expected to enhance CO_2 efficiency in the steel, cement and paper and pulp sector in Europe. Special attention is paid to the use of CCS in Section 5.2. Main conclusions are formulated in Section 5.3., after which conditions for succesfull implementation are mentioned in Section 5.4. Finally, uncertainty of the reseach findings is discussed in Section 5.4.

5.1 Summary of sectoral results

The analysis reveals that opportunities exist to move towards more sustainable manufacturing in Europe leading up to 2050. In the steel, cement and paper and pulp sectors, existing or anticipated technologies can yield a positive impact on CO_2 efficiency compared to the current average plant in Europe.

Table 18 provides an overview[48] of the findings per sector. Technologies are classified as breakthrough technologies (marked by *), potential breackthrough technologies (marked by ^) and alternative technical (back-up) options that are more certainly available or available earlier.

Steel Sector
For the steel sector, HIsarna coke free steelmaking appears to be the most promising in the medium-term (2020-2030).The main features of the technology are that coke is no longer input for the steel process and CO_2 is captured and stored (CCS). An 80% reduction can be reached compared to an average blast furnace. In addition, investment and operational costs lie below average, the latter due to a wider range of (cheaper) inputs that can be used.

In the short run, the Fastmelt process is a valuable option. It is already available on the market and also yields a significant CO_2 reduction compared to the average blast furnace in Europe. Although initial investments costs are relatively high, a main advantage of the technology is that a broader range of inputs can be used for steelmaking, thereby lowering the operational costs.

Finally, top gas recycling is a technological route which has been explored at a LKAB pilot plant (Sweden). It will shortly be demonstrated on a commercial-scale. The technology is more CO_2 efficient than the average blast furnace in Europe. New plants are expected to be built using this configuration.

In the longer run, electrolysis could be a promising option. It means that electricity is used for the reduction process. This would allow for carbon-neutral steel production if the electricity used in the process is produced without CO_2 emissions. The industrial process no longer requires carbon but electrolysis is still in the early stages of development. Without further R&D stimulation, it might, according to some, take over 20 years before the first commercial scale production facility could become operational.

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[48] Most of the technologies are developed within the EU region, except Fastmelt whose process was originally developed in Japan. The underlying reason might be that production capacity in the steel sector is likely to increase in emerging markets so that installations with the latest available technologies are located there.

Table 18 Key findings per sector

Technology	Main advantages compared to reference	Potential drawbacks compared to reference	Technological maturity
	Steel Sector		
Coke-free steelmaking, with or without CCS (HIsarna)*	- 80% CO_2 reduction compared to average blast furnace with CCS, 20% without CCS - Lower investments and operational costs due to broader range of available inputs	- Needs replacement of existing blast furnaces	2010: Pilot phase (NL) 2025: Market deployment
Fastmelt process of direct reduction, with of without CCS*	- 55% CO_2 reduction compared to average blast furnace with CCS, 5% without CCS - Lower operational costs due to broader range of available inputs	- Needs replacement of existing blast furnaces - Higher investment costs	2010: Market deployment
Top gas recycling with CCS*	- 50% CO_2 reduction compared to average blast furnace - Expected to be the standard for newly built plants (retrofit option)	- Higher operational costs	2010: Pilot phase 2020: Market deployment
Electrolysis^	- Probably no carbon is needed in the production process		2010: Not developed (pre-pilot phase)
	Cement Sector		
Magnesium based clinker (Novacem)*	- Over 100% CO_2 reduction compared to average kiln (sink). Avoidance of process emissions, carbonisation of product (no CCS required) - Same investment costs as alternative technologies and operational costs similar to average kiln	- There might be some issues with current market standards on product quality	2010: Pilot phase (UK) 2025: Market deployment
Oxyfuel firing with CCS*	- 90% CO_2 reduction compared to average kiln (almost complete CO_2 capture)	- Higher investment costs than alternatives and higher operational costs than average kiln	2010: - 2025: Market deployment
Biomass and natural gas utilisation	- 35% CO_2 reduction compared to average kiln	- Higher operational costs	2010: Market deployment
Higher use of Portland clinker substitutes	- 10 to 20% CO_2 reduction compared to average kiln	- Limited availability of substitutes	2010: Market deployment
	Paper and Pulp Sector		
Black liquor gasification, with of without CCS (Chemrec)*	- Over 90% CO_2 reduction compared to average production	- No impact on fossil fuel related CO_2 emissions in the paper sector.	2015–2020: Market deployment
Paper drying innovations^	- Would affect the most important source of non-biological CO_2 emissions in the sector		2010: Not developed (pre-pilot phase)

Cement Sector
In the cement sector, the Novacem route of producing magnesium clinker based cement is identified as a promising future technology. It offers lower energy consumption and a huge CO_2 reduction, if not a carbon sink. Process emissions and carbonisation of product during production are avoided, so no CCS would be needed. At the same time cost figures are similar to the existing cement kilns. However, efforts need to be undertaken to make it ready for market introduction and for the products to (better) meet market standards.

In the meantime, the use of oxyfuel would be possible in the medium-term. It is an oxygen fired, limestone based clinker production process. This technology might yield up to 90% CO_2 abatement as it requires CCS. Both investment and operational cost figures are above average though.
Biomass/natural gas utilisation can be an option for companies to enhance their CO_2 efficiency somewhat (35% emission reduction expected). However, operational costs will be rather higher compared to the current average costs.

Finally, increased substitution of Portland cement could yield some CO_2 abatement. Due to a limited availability of alternatives, however, the degree of substitution might only increase from 20% (current EU average) to 35%. Subsequently, the emission reduction potential remains rather limited, i.e. 10 to 20%. Only when significant innovation regarding alternative binders takes place, the abatement potential of such technical option might increase.

Paper and Pulp Sector
Finally, in the paper and pulp sector black liquor[49] gasification with subsequent CCS has been identified as the technology that could be implemented in a relatively short term and allows for significant CO_2 reductions. This option has been developed by Chemrec (Sweden). This process may change chemical pulp production into a carbon sink by capturing CO_2 from black liquor for geological storage. It does require higher initial investment funds and probably somewhat higher operational costs.

If the paper sector wants to focus on CO_2 abatement in the production process, instead of applying CCS, a valuable or most relevant route would be drying processes. Drying of paper represents the bulk (up to 70%) of fossil energy consumption within the pulp and paper sector and subsequently represents the most important source of non-biological CO_2 emissions. In principle, the potential for energy saving in this process is still very high.

5.2 General remarks on the role of CCS

Whereas the technologies that have been identified to enhance the CO_2 efficiency of manufacturing in Europe succeed in reducing some process emissions, they rely heavily on capture and deep geological storage (CCS) of the CO_2 produced in industrial processes in order to ultimately reduce a significant amount of emissions. Only in the cement sector is there an alternative to significantly reduce emissions in the medium-term (Novacem). The concept of CCS still has to be proven to a certain extent.

[49] Black liquor is a major residue of chemical pulping.

The individual steps have all been applied in commercial activities, often for a long time[50] and partly in combination with each other. However, perpetual storage of CO_2 is new and has not been demonstrated in practice before. There is some uncertainty if and how it can be guaranteed that CO_2 injected in deep geological gasfields and aquifers will actually stay there for thousands of years. This can only be estimated using model simulations and the chance maximised by the application of a stringent set of storage site selection criteria and storage reservoir closure and abandonment criteria. The probability is more predictable and the criteria can more easily be met for geologically intensively explored, intrinsically gas-tight natural gas fields than for aquifers.
Criteria and protocols for reservoir behaviour modelling, injection, abandonment, monitoring are currently being developed and embedded in legislation. Initators will have to prove that the probability of CO_2 escaping is similar to the probability of accidents at industrial facilities[51].

This lack of solid proof of the viability, reliability and safety of the concept has resulted in public concern and hesitation by environmental NGOs to rely on such a technology. Besides, the potential of CCS is probably not sufficient enough to reach an economy-wide reduction of 80-95% in industrial CO_2 emissions as required in the period up to 2050. The latter is due to:

- The limited capacity of sufficiently safe deep geological storage reservoirs.
- Competition with the power sector to acquire storage capacity.

Estimations by the EU financed GESTCO and Geocapacity projects of deep geological storage capacity for CO_2 in the EU amount to a capacity of approximately 120 Gtonne CO_2: 96 Gtonne CO_2 capacity in deep saline aquifers, 20 Gtonne in oil and gas fields and 1 Gtonne in unmineable coal fields. This estimate is said to be conservative. Total EU CO_2 emissions from large point sources (> 0.1 Mtonne/year) are estimated at 2 Gtonne/year, approximately 50% of which is emitted by power plants. This would imply that the storage capacity in the EU corresponds to 60 years of current annual CO_2 from large point sources.

It should be noted, however, that these estimates are shrouded in some uncertainty as they are based on a limited amount of data. In addition, it is not possible to estimate which part of these storage sites meet the safety and geology related site selection criteria such as:

- Cap rock thickness.
- Physical characteristics of the cap rock (plasticity and response to pressure changes).
- Chemical characteristics of the cap rock, e.g. resistance of cap rock to chemical reaction with CO_2.
- Faults in or just above the cap rock.

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[50] The capture of CO_2 has been commercially applied for decades in hydrogen production, ammonia production, beer brewing, ethanol production and coal fired power plants (e.g.). Transports by pipeline, by road and by rail have been applied commercially as part of respectively CO_2 utilization in enhanced oil recovery and use of CO_2 in for example beverage industries and horticulture.
CO_2 injection has been applied commercially as part of enhanced oil recovery in numerous projects in the USA, Venezuela, Algeria.

[51] Both IPCC report and Australian legislation demand a probability of 20% or less that a maximum of 1% of the stored CO_2 escapes within a 1,000 year period. This is equivalent to a possibility of approximately $1 \cdot 10^{-6}$ that CO_2 escapes.

Additionally, for gas and oil fields there is no indication concerning:
- The number of existing or abandoned wells.
- The accessibility of the wells for monitoring.
- The suitability of well casings and well plugs for long-term storage of chemically reactive and corrosive high pressure CO_2.
- Use for evaluation of field suitability for storage.

As a consequence no indication can be given about the actual suitability of the identified potential reservoirs.

Finally, there is also some discussion about the attractiveness of storage in aquifers. In general, storage in depleted and abandoned gas fields seems more attractive compared to storage in aquifers (see Amesco, 2007):
- Available information:
  Storage in depleted gas fields can make use of a long track record of site characterisation with the main focus on the static and dynamic properties of the reservoir. It has been shown that the behaviour of the reservoir during CO_2 injection can be well predicted from the gas production history. These data and information are mostly missing for aquifers.
- Proof of containment:
  The very presence of gas trapped in reservoirs for geological time periods indicates that these structures can contain CO_2 as well, provided that the sealing properties of the cap rock and bounding faults have not changed due to gas production, the cap rock entry pressure for CO_2 is not exceeded, and the sealing properties are not affected by chemical reactions with CO_2 loaded fluids. The containment of CO_2 in aquifers would have to be proven with the help of additional field and laboratory measurements.
- Reservoir conditions:
  In most abandoned gas reservoirs in the Netherlands, for example, the pressure has dropped to very low levels, 30 to 50 bar, which is 100 to 300 bar below the initial reservoir pressure. This pressure window can be used for injecting CO_2 until the initial reservoir pressure is reached, preventing any negative effect on the seal, e.g. fracturing will be prevented. Injection in aquifers starts at the initial (hydrostatic) pressure and builds up pressure well above it, with potential adverse consequences for the seals.
- Reservoir properties:
  In general, the porosity and permeability of gas reservoirs is higher than those of the water-saturated alternatives. This will result in a larger capacity and better injectivity for CO_2 storage than in aquifers. In gas reservoirs there is less free water than in aquifers, which will limit the corrosion of well casing and degradation of the well cement. On the other hand, the high water saturation of aquifers promotes the dissolution of CO_2 in water, making the CO_2 less mobile.

Given the uncertainties about actual suitability of the identified reservoirs and the question whether storage in aquifers is desirable, the estimated storage potential of 120 Gtonne in the EU seems optimistic. Therefore, one may want to reconsider the current role of CCS, which is used particularly in the power and heat sector. If storage potential is limited and uncertain and if there are alternative emission reduction options for power and heat generation, while for industrial processes low carbon intensity processes are less readily identifiable, one may want to consider setting geological storage capacity for CO_2 aside for storage of CO_2 captured at industrial processes.

5.3 Main conclusions

This study indicates that significant emission reductions seem possible in the steel, paper and cement manufacturing, together accounting for 41% of the European industrial CO_2 emissions. Based on the available information, several promising technologies with repect to CO_2 efficiency have been identified in these sectors. They seem to have the potential to produce significantly lower CO_2 emissions per unit of product compared to the current average production plant in Europe. Since these technologies are currently in pilot stages of technological development and are expected to become commercially available between 2020 and 2030, a significant reduction in CO_2 emissions until 2050 seems viable.

Broadly speaking, the identified technologies have been classified into three categories:

– Breakthrough technologies
  In the context of this study, technologies are defined as breakthrough when:
  - They yield CO_2 emission reductions of 25% or more compared with current average technology.
  - Become commercially available in 2020–2030[52] and have the potential for wide implementation in the sector in the period up to 2050.
  - Can be expected to be economically competitive compared to the current and future reference technologies.

– Back-up technologies
  These are technological options that fit with existing production processes but do not yield the required CO_2 reductions and/or come at higher costs. They might still be needed in case a particular breakthrough technological innovation turns out to be less successful than expected and for reduction of CO_2 emissions of reference technology installations still existing in 2050.

– Potential breakthrough technologies
  These technological routes might turn out to be longer-term breakthrough technologies (beyond 2030-2050) if additional R&D is stimulated. They are not in the pilot stage yet or are being applied in other sectors than those considered in this study, but seem to have the potential for realisation of the required CO_2 reduction of 80-95%.

With regard to the types of technologies that can be applied we distinguished between:

– Use of energy carriers with a lower carbon intensity in existing technology, e.g. electricity or biomass instead of natural gas or coal.
– Combination of existing technology with capture of produced CO_2 for perpetual deep geological storage.
– Design a new process which is intrinsically more energy efficient and/or carbon-neutral.

The development of breakthrough technologies aimed at yielding intrinsically more energy efficiency and/or carbon-neutrality seems limited to one development in the cement sector; work on magnesium based clinker which can be a substitute for Portland clinker. In the steel sector, the development of an intrinsically carbon-neutral process in the shape of electrolysis is still very much in the embryonic phase and could be considered a potential breakthrough technology. For the paper sector it would be worthwhile to further explore possibilities for intrinsically more energy efficient paper drying

[52] This means that they are currently at least in or close to the pilot stage of technological development.

processes. Current energy prices in the last decades have not given enough incentives.In the future, CO_2 prices and costs for fuels and electricity could boost incentive to accelerate the development of the two potential breakthrough technologies identified for the steel and paper sectors.

The utilization of low carbon intensity energy carriers such as biomass and natural gas only seems a back-up measure for the cement and steel sectors. In the cement sector, it would have limited impact on total CO_2 emissions as these are dominated by raw materials related process emissions. In the steel sector, the technical possibilities of utilising low carbon intensity energy carriers in blast furnaces is limited. In the paper sector, biomass already is the main fuel for the most energy-intensive processes.

Possibilities for significant CO_2 emission reduction through the implementation of CCS based breakthrough technologies exist in all three sectors, partly in combination with process innovations in cement and steel sector.

The general conclusion of our inventory is that the innovative technologies currently under development have the potential technically for realising very significant reductions in industrial CO_2 emissions. At the moment most of these innovations rely heavily on CCS in order to achieve this.

The dependency of the breakthrough technologies under development on CCS yields two specific uncertainties and possible disadvantages:
- The lack of solid evidence of the viability of long-term storage has raised public concern and hesitation by environmental NGOs about relying on such a technology.
- If CCS is to be applied, attention must be paid to the possibility that there may be limited storage capacity for CO_2 sequestration. If so the question is whether it should be reserved for industrial use instead of application in the energy sector (coal), where more CO_2 abatement options seem to be available.

5.4 Conditions for succesfull implementation

Technological innovation is crucial to realise significant CO_2 reductions up to 2050. In this study, we have already identified various promising initiatives. For a succesfull use of the technologies, it is necessary to stimulate (further) technical development and create market conditions with a preference for low CO_2 emission technologies.

In this regard, favourable market conditions are crucial. The prevalence of low energy prices has been an important aspect that has shaped the direction of technological developments so far. Innovation mainly focused on fossil fuel based processes instead of on alternative energy sources. This might change in the future when energy prices rise. Technologies based on renewable energy might become much more interesting for sectors to look at under that circumstances. The sufficiently high CO_2 price is also relevant for inducing further R&D on low carbon technologies. By creating a market for CO_2, the EU has created additional incentives to reduce emissions. It should ensure that the market keeps providing incentives to CO_2 reductions in order to stimulate innovation, in part by setting an ambitious emission reduction target. In some cases, additional regulation might be needed to stimulate the uptake of innovative technologies. For example by tightening BAT REFs for new plants.

In addition, further research is needed to make promising CO_2 abatement routes ready for market deployment. Therefore, the EU must (continue to) provide additional funds for R&D. In well functioning markets, one could argue, innovation will occur continuously. On the other hand, sectors might need additional support for investments in pilot plants and especially demonstration plants, which have a high capital requirement and represent significant risks (success is not guaranteed). Such funds have already been made available by the EU and several EU member states for demonstration projects in the steel sector, to be initiated as part of the ULCOS programme. Similar funding might be also be required in the cement sector for demonstration of the Novacem product and/or oxyfuel fired Portland kiln technology. In pulp production black liquor gasification and associated CCS might need further support. Also, targeted R&D programmes could increase the supply of new technologies. Options such as electrolysis and paper-drying innovations will require more effort and time to become technologically mature. They are still in a pre-pilot phase at the moment.

Finally, there might be a priority issue when a particular technology is scarce and can be applied in several sectors. For example, there seem to be limited storage locations for CCS that meet safety requirments[53]. The question is whether they should be reserved for industrial use instead of application in the energy sector (coal), where more CO_2 abatement options seem to be available.

5.5 Uncertainty

In this report we adopt a long-term perspective of technological innovations regarding CO_2 efficiency. We have painted a picture of promising technological options, based on our expertise, conversations with stakeholders and using as many information sources as possible. Of course, it is always difficult to look at future developments. No one has a monopoly on wisdom there. The report reflects current knowledge of future developments and therefore inherently contains uncertainty. There is no guarantee that the technological routes we mention will actually be the ones that will have been realised in 20 or 30 years' time. The chance of actual realisation will depend on the pace of technological development in the coming years and the way governments design markets and stimulate innovation.

[53] Offshore storage and storage in deep (> 1 km) gas or oil that are located in non-tectonically active areas and are capped by a geological salt layer or geological layer of similar specifications.

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