Opportunities for reducing CO$_2$ in European industry until 2050
- a synthesis of industry analyses within the Pathway project

European industry has the potential to contribute substantially to both reduced CO$_2$ emissions and development towards sustainability. However, to reach low emission levels, all types of measures, including structural change, energy efficiency improvements, fuel substitution and carbon capture and storage are needed. Energy-intensive industries play a key role in this process, and have substantial potential for large step-wise reduction measures. However, implementation of these measures is crucially dependent upon energy market conditions and infrastructure, and therefore on interactions with other parts of the energy system.

Within the Pathway project a number of sub-projects directed towards the industrial sector have been included, in which the development of specific industrial sub-sectors and/or types of measures for reducing CO$_2$ emissions are studied. These results provide a basis for estimating the potential contributions of technological and structural changes within industry to the development of overall energy systems pathways. In this report, a synthesis for the entire European industry sector is presented that strive to utilize fully the knowledge gained in all these studies, supplemented with data in the literature.

This report is a result from the project Pathways to Sustainable European Energy Systems – a five year project within The AGS Energy Pathways Flagship Program.

The project has the overall aim to evaluate and propose robust pathways towards a sustainable energy system with respect to environmental, technical, economic and social issues. Here the focus is on the stationary energy system (power and heat) in the European setting.

The AGS is a collaboration of four universities that brings together world-class expertise from the member institutions to develop research and education in collaboration with government and industry on the challenges of sustainable development.
Opportunities for reducing CO$_2$ in European industry

- a synthesis of industrial analyses within the Pathway project

AGS Pathways report 2010:EU3

Eva Andersson
Ingrid Nyström
CIT Industriell Energi AB, Göteborg, Sweden
This report can be ordered from:
AGS Office at Chalmers
GMV, Chalmers
SE - 412 96 Göteborg
alexandra.priotna@chalmers.se

or ordered from
www.energy-pathways.org
The research program Pathways to sustainable European Energy Systems (the Pathways project) is part of the international cooperation Alliance for Global sustainability (AGS) and managed by Chalmers. The Pathways project is a five year project with the overall aim to evaluate and propose alternative robust pathways towards a sustainable energy system with respect to environmental, technical, economic and social issues. The focus is on the stationary energy system (power and heat) in the European setting.

Within the Pathway project an analysis group for industry and a number of sub-projects directed towards the industrial sector has been included. This report includes a synthesis of the potential contribution of technological and structural changes within industry to the development of overall energy systems pathways, based on the analytical results of these sub-projects and on data in literature.

_Eva Andersson and Ingrid Nyström_
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Within the Pathway project, an analysis group for industry and a number of sub-projects directed towards the industrial sector have been included. In these sub-projects, the development of specific industrial sub-sectors and/or types of measures for reducing CO2 emissions is studied in great detail. These studies have focused on energy-intensive industry sectors, with a high share of process-dependent energy use and relatively few, albeit large, industrial plants. Furthermore, a top-down analysis of the European industrial sector as a whole has been made. Thus, the methodological approaches used in these sub-projects vary significantly.

In addition to the analytical results from each sub-project, the results provide a basis for estimating the potential contributions of technological and structural changes within industry to the development of overall energy systems pathways. The challenge is to utilize fully the knowledge gained in all these studies, so as to reach a coherent and well-founded synthesis for the entire industry.

European industry has the potential to contribute substantially to both reduced CO2 emissions and development towards sustainability. However, to reach low emission levels, all types of measures, including structural change, energy efficiency improvements, fuel substitution, and carbon capture and storage (CCS), are needed. A development towards low emission levels require considerable structural changes in terms of product and process developments, technological advances, committed efforts both within industry and amongst policy makers, and large investments.

Energy-intensive industries play a key role in this process, and have substantial potential for large step-wise reduction measures. However, implementation of these measures is crucially dependent upon energy market conditions and infrastructure, and therefore on interactions with other parts of the energy system.

Industrial CO2 emissions are shown to have potential for large reductions in both pathways studied. Total direct emissions in 2050 could be up to 50% and 60% lower in the Policy and Market pathways, respectively, as compared to the corresponding values for year 2000. In the Policy pathway, energy efficiency improvements and the use of biomass for energy are important means. The lower levels of direct emissions in the Market pathway depend primarily on increased implementation of CCS and on conversion to efficient electricity use. Furthermore, the industry may play a significantly impact indirect emissions.

This synthesis is performed as an ex-post exercise, based on analyses presented in other research studies. There are significant uncertainties associated with the presented results. Nevertheless, the overall results are useful for increasing understanding of the roles of industry in a climate policy context. For the future, it would be valuable to use the experiences gained here to design the synthesis work in parallel to the analytical work and construct it on a more rigid methodological framework.
The European industrial sector as a whole plays an important role for the European energy system and its emissions of greenhouse gases. Although the climate issue is dependent on six different greenhouse gases, the primary focus is here on emissions of carbon dioxide (CO$_2$). Direct emissions of CO$_2$ from the industry account for slightly more than 20% of total European CO$_2$ emissions. Furthermore, industrial production and energy use have large indirect impacts on emissions. Activities with indirect effects include, for instance, electricity use, co-generation and, not the least, the design of energy-using products. Compared to, for instance, the residential sector, the industry sector, as a whole, is extremely heterogenous and complex, with a large diversity in processes and energy use.

The role of industry in reaching a sustainable energy system is thus multifaceted. As a result of the complexity, few long-term energy systems studies include a thorough analysis of the industry and its potential for contributing to the reduction of greenhouse gases.

1.1 Background and context

The research program Pathways to sustainable European Energy Systems (the Pathways project) is part of the international cooperation Alliance for Global sustainability (AGS) and managed by Chalmers. The Pathways project is a five year project with the overall aim to evaluate and propose alternative robust pathways towards a sustainable energy system with respect to environmental, technical, economic and social issues. The focus is on the stationary energy system (power and heat) in the European setting. The approach of the project is specifically to base evaluations on detailed descriptions of the present energy system and to focus on how the present system can transform into a more sustainable future.

Within the Pathway project an analysis group for industry and a number of sub-projects directed towards the industrial sector has been included. In these sub-projects, the development of specific industrial sub-sectors and/or types of measures for reducing emissions is studied at great detail. Furthermore, a top-down analysis of the European industrial sector as a whole has been made. The methodological approaches used in these sub-projects thus range over a wide spectrum. In addition to the analytical results of each sub-project, their results give a basis for estimating the potential contribution of technological and structural changes within industry to the development of overall energy systems pathways.

1.2 Analysis presented in this report

The purpose of the analysis reported here is threefold: 1) to describe and summarize the industry related analyses made within the
Pathway project; 2) to synthesize and discuss these results, based on different methodological approaches and; 3) to relate the results to the overall pathways towards sustainability, developed within the Pathway project.

In doing this, the analysis provide an overview of the European industry’s potential contribution to reducing CO₂ emissions and a basis for continued efforts to provide coherent and extensive systems analyses of the entire industrial energy system.

In this report, we firstly give a background by describing the pathways towards a sustainable energy system developed within the Pathway project and their implications for industry (Chapter 2). In Chapter 3, a methodological overview for analysing industrial energy use, in general and in the analyses presented here, is given. Chapter 4 describes the top-down analysis of European industry, included in the Pathway project. The major part of the study is then presented in Chapter 5. In this chapter, top-down and bottom-up analyses of each industrial sub-sector are described and discussed separately. The qualitative implications for the sectors’ contribution to reducing CO₂ emissions are discussed and, finally, some quantitative conclusions are drawn. Chapter 6 includes concluding overall results for the industry as a whole, together with a discussion.

The analysis is primarily based on industrial research within the Pathways program, but supplemented by data and results found in the literature.
The concept of pathways to a sustainable energy system is used within the Pathway project to depict alternative routes towards a more sustainable development. In this concept it is acknowledged that we cannot at this stage fully describe an energy system that is sustainable. We can, however, determine conditions and directions that are necessary for developing a more sustainable society and determine steps that should be taken to move in this direction. Furthermore, these steps can be taken along different routes or pathways.

Within the project, two principally different routes have been developed to illustrate different approaches in climate and energy policy. The two pathways are labeled the Policy pathway and the Market pathway. Both pathways are related to a baseline development. The pathways considered differ in terms of which types of policies used (economic and other) to steer the energy system development towards sustainability, but are based on the same general development of energy markets (that is, development of the prices of crude oil, natural gas and coal). These prices are based on projections by EU [EE&TT, 2007].

2.1 The Policy pathway

The Policy pathway is based on a development in which there are parallel targets for reduction of CO₂ emissions, for improvements in energy efficiency and for increasing the use of renewable energy sources. This means that the policy package used is assumed to be comparably complex and diverse, and in some cases with overlapping purposes and effects. One could state that in this pathway, the politicians to a higher degree than in the Market pathway, strive to impact which measures that should be taken to achieve a sustainable energy system. This pathway is in line with current EU politics. Thus current targets for 20% renewable energy, 20% energy savings (compared to a baseline scenario) and 20% reduction of GHG are included and met. In the Policy pathway, the measures taken are assumed to be relatively demand-side oriented and, compared with the Market pathway, a substantially larger share of CO₂ reductions is achieved by energy savings. Furthermore, it is assumed that policy instruments exist that increase direct use of renewables on the demand side, such as biofuels in the transportation sector and biomass in the buildings and industrial sectors. Even though the Policy pathway has much focus on the demand side, the supply side has to undergo significant changes as well, including conversion to renewable electricity and district heating production and introduction of carbon capture and storage (CCS).

The Policy pathway will lead to initially faster decreasing CO₂ emissions than the Market pathway. By 2050 both pathways will, however, reach the same emission levels. The policy measures in this pathway are assumed to generate a lower cost for CO₂ emissions than in the Market pathway, since the reductions are partly achieved through other policies.
Electricity and biomass prices are assumed to be somewhat lower, while the extra incentive for green electricity generation is assumed to be higher. The policy packages used for reaching the targets for energy efficiency improvements are to a large extent assumed to be non-economic and include for instance standards and other regulations on the specific plant or technology level.

For the industrial sector the Policy pathway is assumed to imply:

- Energy efficiency improvements in all sub-sectors close to the technical potentials. This includes both general efficiency improvements and successful technology shifts.
- Increased use of biomass for process heat and CHP, as a result of specific regulation increasing demand-side use of renewable energy carriers.
- Moderate impact on the use of district heating and heat-pumps in industry.
- Energy efficiency improvements lead to less surplus heat available, but at higher temperature levels. In some industries, surplus is instead available as fuel or increased electricity production.
- Implementation of CCS from 2020, but to a lesser extent than in the Market pathway. This depends partly on lower CO2 price, partly on less available surplus heat (as a result of efficiency improvements).

2.2 The Market pathway

The main idea behind the Market pathway is that targets are set for CO2 reductions only. The policy package used is in this case primarily assumed to be based on a developed emission trading system, leading to equal CO2 cost between sectors and emission sources (or possibly a levelled CO2 tax). The choice of emission reduction measures is then to a larger degree determined by the market. In addition, policies for utilizing a gradually CO2 free supply side for reducing CO2 emissions further (e.g. through conversion to electricity), are assumed to be introduced. However, there are no explicit targets or policy instruments for promoting energy savings or use of renewable energy.

In the Market pathway, the policies are thus assumed to move the system primarily towards supply-side oriented reduction measures. Measures include, for instance, fuel switch towards less CO2 intensive fossil fuels, increased use of renewables and nuclear energy and the implementation of CCS. The demand side contributes to decreasing CO2 emissions by converting to district heating and efficient electricity use, such as heat pumps. Furthermore, an intensive electrification of the transport sector is assumed. The pathway includes, of course, also demand-side energy efficiency improvements, but at a significantly lower level than in the Policy pathway and primarily before 2020, when supply-side options (e.g. CCS) are assumed to be less available.

Policy measures in this pathway are assumed to generate a relatively high cost for CO2 missions and, as a consequence, higher price levels for both electricity and biomass, compared to the Policy pathway.

For the industrial sector the Market pathway is assumed to imply:

- Implementation of CCS from 2020 at a higher level than in the Policy Pathway, primarily because of higher CO2 price levels.
- Increased efficient use of electricity, for instance heat-pumps, and of district heating for low-temperature heating demands.
• Moderate increases in biomass use directly within industry.

• Surplus heat available from the industry, primarily used for CCS and for increasing district heating deliveries.

• Energy efficiency improvements compared to Baseline, but considerably less than in the Policy pathway.

2.3 Baseline development

For the comparison of pathways over time, a Baseline scenario for energy systems development is needed. In order to be a clear contrast to the sustainability pathways, the Baseline scenario used in the Pathway project represents a situation without any imposed sustainability targets, that is, without any imposed cost of emitting CO₂. Hence, none of the European Union’s energy and sustainability targets are met.

The baseline used should, thus, not be interpreted as a projection of expected development, since already today there are a multitude of policies available throughout the EU that strives to push the development towards sustainability.

For the industrial sector such a development imply a continued increase in total energy use and CO₂ emissions. However, also at historical rates, overall productivity increase has lead to substantial decreases in specific energy use and CO₂ emissions within industry. In the Baseline scenario a similar development is assumed, based on changes in relative energy prices and, primarily, so-called autonomous energy efficiency improvements (including effects of structural change). See further Chapter 4 and 5.
3. INDUSTRIAL CONTRIBUTION TO THE REDUCTION OF CO\textsubscript{2} EMISSIONS - methodological aspects

3.1 Development of industrial energy use and emissions

Development of total direct energy use within the industrial sector as a whole depends on the development of total production volume, industrial structure (types of products produced) and specific energy use for producing each product. This principal division between influencing factors is true both on a very aggregate level and for a single industrial sub-sector.

The development of carbon dioxide (CO\textsubscript{2}) emissions from the industry, in addition to the factors above, also depends on the carbon intensity of energy carriers used, including the effect of applying carbon capture and storage (CCS) to industrial emissions.

Finally, the industry will also have large indirect impacts on total emissions via their products. The development and marketing of climate smart products, such as energy efficient refrigerators or light-material cars, will be of high importance to the possibility to reach low emission levels. However, the potential reductions are taken into account in the analysis of other sectors and will not be discussed further in the analysis presented here.

The contribution from the industrial sector to changes in total CO\textsubscript{2} emissions related to its direct energy use can thus be divided between the following types of changes:

- Change in production volume. The relation is straightforward when studying total energy use for producing a specific quality of paper, whose production is expressed in physical tons. At an aggregate level, total production volume can be expressed in monetary terms only (mostly as value-added), since adding different physical production volumes is in general impossible, also within one specific industrial sub-sector. Changes in production volume in terms of value-added may, however, be unrelated to the amount of energy used in the production processes, or rather, the relation is extremely difficult to determine.

- Structural change – between industrial sectors and within a specific sector. For the entire industrial sector, structural development concern for instance the share of energy-intensive steel-making compared to that of computer processors production. On a more disaggregate level it may instead be changing bleached printing paper for unbleached or development of new products that impact the sector’s energy use. The changes may be in either direction. It is not uncommon that new products (often with higher value-added) demand further “refining” and thereby more energy using production processes.
- Energy efficiency improvements, resulting in lower net energy use per produced unit. For the industry, efficiency improvements may include also increased energy deliveries to other parts of society. Efficiency improvements may be a result of general modernization of production, specific energy efficiency measures and technological development. Radical energy efficiency improvements are often linked to technological inventions that change production processes in a more fundamental way. In these cases the change may be closely linked to product development and structural changes on the microlevel (e.g. changes in raw-material).

- Decreasing the CO₂ intensity of energy use. This factor may be sub-divided into two different types of changes:
  
  o Increasing the share of less CO₂ intensive energy carriers, such as renewable energy carriers, but also shifts from coal to natural gas. Substitution of fuels for district heating or electricity decrease the direct CO₂ intensity of the sector, but may lead to both increasing and decreasing CO₂ emissions in total, depending on the CO₂-intensity of district heating and electricity production.

  o Carbon capture and storage (CCS), which result in a net decrease in CO₂ intensity without change of energy carriers. However, CCS also, in addition to reducing CO₂ emissions, increases total energy use.

Even though this principal division may seem simple enough, it represents in reality highly complex relations. The industrial sector as such is extremely diverse and heterogenous, both in products, processes and types of energy used. Consequently, analyzing potential future developments of energy use and CO₂ emissions from the industry is complex and the uncertainties are large.

Analyses of industrial energy use may either be directed towards estimating the potential contribution from the industry in reaching the targets for reducing CO₂ emissions or towards estimating the expected development, depending on the choice of policy measures, energy market development and economic conditions. Both perspectives can, in addition, provide information about key “success” factors and technologies as well as potential barriers. Both perspectives are relevant and valuable to policy makers and industry. The perspective taken does, however, impact the methods used for the analyses.

In generalized terms one may categorize the methods used as either top-down or bottom-up. Top-down versus bottom-up methods, and the resulting “gap” in results have been widely discussed in literature over the last 20 years. Direct links to analyses of industrial energy use are fewer though. A more thorough review has been made within the Pathway project and can be found in Algehed et al [2010]. Top-down studies are based on economic theories and strive to describe the expected development of demand based on price elasticity and empirically determined parameters for so called autonomous energy efficiency improvements (AEEI).

The AEEI constant is an aggregate representation of all those changes in specific energy use per added value that are independent of energy price development. This type of factor is widely used in economic modelling to take into account both increasing value added and more efficient energy use. The constant thus represents structural change, product development, energy technology development,
improved knowledge about energy efficiency improvement options, side-effects from other environmental regulations etc, as long as these changes cannot be directly related to changes in energy price.

In principle, a top-down approach capture all types of factors above, since change in relative prices affect both structural development and technological change. However, since parameters used are based on historical development it is often argued that these badly account for changes that has not been experienced before. Examples may be large increases in relative energy prices, radical technology shifts, such as CCS, or major policy changes. Top-down studies, thus, tend to be conservative when it comes to technological and policy development. Furthermore, they are restricted to simulations of financial policy instruments and lack technological detail. They can therefore not account for constraints based on thermo-dynamical and/or process specific limitations. Finally, data issues in determining robust values for price elasticity are numerous.

Bottom-up studies include a wide variety of studies, ranging from bottom-up modelling studies of entire sectors to detailed engineering studies of specific processes. They have, however, a common basis in focusing on the technological (or techno-economic) potential from an engineering perspective. The perspective of bottom-up analyses is, basically, to compare alternative technological options for achieving the same energy service, and evaluate which are more interesting from an environmental and/or economic perspective. Bottom-up studies, thus, often include microeconomic analyses, but lack macro-economic effects or feed-back. As a result, bottom-up studies tend to be conservative in the sense that they are based on current production structure and products. In addition, data issues are, of course, a major source of uncertainty also in these studies.

In addition to top-down and bottom-up approaches, hybrid methods and models are being developed and implemented. More often, hybrid models take the perspective of top-down methods, striving to analyze the expected development, even when the models as such are based on a bottom-up framework. However, hybrid models generally include a higher level of technological detail and physical constraints.

3.2 Analyzing energy use from two perspectives - methodology

Analyses of industrial energy use within the Pathway project are based on both top-down and bottom-up analytical tools and methodologies. For some sectors a hybrid capital vintage approach has been applied as well. The top-down analysis is based on a model of the entire European industry sector, whereas the bottom-up studies concern specific technologies (such as CCS), specific countries (e.g. Germany) or specific industrial sub-sectors (such as the pulp and paper industry). These studies have been focused on energy-intensive industry sectors, with a high share of process dependent energy use and relatively few, but large, industrial plants (see also Methods and Models, 2010). The challenge taken is to fully utilize the knowledge gained in all these studies, and to reach an as coherent and well-founded synthesis for the entire industry as possible.

The synthesis presented in this report is performed in the following three steps:

1) Establishing a starting point for the development of industrial energy use, based on results from the top-down industrial model.
2) Providing a coherent overview of potential changes in energy use and CO₂ emissions, based on bottom-up analyses.

3) Relating the top-down and bottom-up results to each other in order to estimate a development for each of the pathways used.

**Establishing a starting point**

The starting point for the synthesis is the results of the top-down model of the European industry, in which the contribution from industry to CO₂ emission reductions is estimated (see Figure 1). This analysis does not take sector specific constraints and conditions into account, but gives a general direction for development of industrial energy demand, given the development of production and energy markets. Furthermore, for the synthesis it provides a necessary complement to the bottom-up analyses, since the latter do not include all sub-sectors and aspects of development. For this reason, the method is described in relative detail in Chapter 4.

**Changes in energy use and CO₂ emissions, based on bottom-up analyses**

The other approach used is based on a range of bottom-up (or hybrid) estimates of techno-economic potentials for emission reductions within each single industrial sub-sector. Most of the industry related studies within the Pathway project are based on a bottom-up approach. The Pathway results thus give the basis for this approach, especially for the energy-intensive industry. These results are complemented with data and results from literature. Measures, which are general, and not process or sub-sector specific, are discussed for the industry sector as a whole.

For each industrial sub-sector (e.g. primary metals sector) potential changes in each of the factors above are discussed. The primary focus is, however, on the potential for efficiency improvements and decreasing the CO₂-intensity of energy use. Since the potential for CCS linked to industrial energy use has been widely studied within the Pathway project, fuel

![Figure 1. Outline of synthesis methodology](image-url)
substitution and CCS are treated separately (see Chapter 5). The refinery sector is treated slightly different since this sector is not included in the top-down model. The refinery sector is therefore analyzed from a bottom-up perspective only (see Figure 1). The purpose of this analysis is to provide an overview of overall sector potentials and each study is described only briefly. For a more detailed description of industrial bottom-up analyses within the Pathway projects, see included references.

When striving to synthesize the results from bottom-up analyses, the complexity of industrial development and energy use becomes clear. To synthesize results from specific studies into overall potential for improvement, the following aspects should be taken into account:

- **Future volume.** The potential for improvements should be related to future production. Bottom-up potentials are mostly based on current production volume and structure. When possible, the potentials have been adapted to account for future development of energy use.

- **Additivity.** The potentials for different measures, applicable to the same sub-sector, are often not (or only partly) additive, which makes it necessary to have a thorough process understanding when comparing potentials quoted in different sources. Similarly, potentials may be dependent on that other measures have already been implemented.

- **Direct and indirect effects.** Measures within the industrial sector contribute to reductions through both direct and indirect effects on total energy use and CO₂ emissions. To fully account for indirect effects an integrated analysis is needed, which in this project is accomplished through the Pathways synthesis.

- **Timing.** The potential for implementing measures, especially in capital-intensive industry sectors, is to a high degree dependent on the technical status of current technologies and will thus develop over time. In the Pathway project this linkage between current infrastructure and future development has been in focus, also for industrial sub-projects. However, the translation of specific results into overall development over time is not straight-forward.

These aspects are included in the synthesis presented here. However, within the limited resources of this project, the inclusion has been based on a qualitative discussion resulting in estimates rather than strict and detailed calculations.

### Estimating the development for each pathway

In a final synthesis, the top-down and bottom-up results for each industrial sub-sector are related to each other and the development for each of the pathways used is estimated. The pathways differ in terms of energy policies implemented, which directly impact both the *level* and type of measures that can be expected to be implemented and thus the techno-economic potential.

This industrial synthesis is primarily *qualitative*, including a discussion about the order of magnitudes and types of measures included in each of the approaches. The discussion focus on which principal adjustments of the top-down results that are needed to account for the findings and sector-specific knowledge included in the bottom-up analyses. Generally speaking, the following four types of adjustments are discussed:

- Adjustments of the baseline development, in cases with a non-realistic development, depending on the lack of sector specific constraints in the top-down model.
- Adjustments of the level of energy efficiency improvements, when technical potentials found in detailed sector analyses are not compatible with top-down results.

- Adjustments to account for policy effects that are not included in the model. This type of adjustments is primarily made for the Policy Pathways, in which a larger share of policies used is assumed to be non-economic and thus not accounted for in the top-down model.

- Adjustments to account for some specific technological shifts that are less likely to be mirrored by historical values on elasticities and AEEI. These include primarily fuel substitution for biomass and the introduction of CCS.

The adjustments discussed should be seen in the light of two aspects fundamentally connected to the differences in methodologies. Firstly, the top-down analysis is based on projections of value-added, which are assumed to continue to increase. However, the implications for physical production are not defined. The bottom-up analyses can, on the other hand, be related to physical production only. Secondly, the basis for comparison is a baseline development without sustainability targets. Also in such a baseline development, energy efficiency improvements would take place. In the top-down model these are included as part of the effects of the AEEI and price elasticities. How these efficiency improvements relate to the bottom-up potentials are not evident.

Finally, based on the qualitative discussion, a rough quantitative estimate is made. The purposes of this estimate is partly to give the order of magnitude for the industry’s contribution as a whole, partly to provide the input necessary for constructing the Pathway synthesis of the entire European energy system. In this estimate also the linkages between industry and other sectors, such as the electricity and district heating sectors, are taken into account. The final numbers used are of course highly uncertain.
4. TOP-DOWN MODELLING OF INDUSTRIAL ENERGY USE

4.1 Model and model data

One of the approaches used to analyse the development of industrial energy use within the Pathway project is a top-down model of European industry [Karampoutakis 2008, European Energy Pathways, 2010]. It is based on conventional econometric forecasting coupled with parameterization of autonomous technology improvements.

In the model, energy use and CO₂ emissions are calculated as a function of production, energy prices, energy price elasticities and autonomous energy efficiency improvement (AEEI) constants. Increasing production levels thus push energy use and CO₂ emissions upwards, while relative price increases for energy and energy efficiency improvements (independent of energy prices) hold them back. When modelling pathways with higher cost increase for CO₂ intensive energy carriers, model results will also include effects of fuel substitution. No feed-back mechanisms – in terms of production levels or technological efficiency – between industrial sectors or with other sectors in the economy are included.

The model represents industry in the 25 member states of the EU in 2005, divided between two geographical regions – old member states (EU15) and new member states (NMS 10). For both regions the model includes ten industrial sub-sectors (mining, food, textile and leather, paper and printing, chemicals, non-metallic minerals, steel, non-ferrous primary metals, equipment goods, and other industries). Refineries are not included in the model.

The development of production in terms of value-added in these sub-sectors is the main driver of the model and assumed to be the same in all pathways studied. In the analysis, projections of future production are based on European Energy and Transport Trends, until 2030 [EE&TT, 2007]. Between 2030 and 2050, production levels are assumed to continue to grow at rates slightly lower than those during 2000-2030. According to these projections added value of European industrial production will increase from €1685 billion/yr in the year 2000 to €3562 billion/yr in 2050, which is an increase of 111 % for the industry as a whole. The development varies, however, between sub-sectors (see Table 1).
Since development of production volume is expressed in terms of value-added, the projected increase can be materialized in terms of increased production volume of current product structure and/or increased production of products of higher added value. The assumption by EE&TT is that there will be a significant restructuring towards sectors and products of higher value added.

Energy demand in the model is divided into coal, oil, natural gas, electricity, and others, where “others” include primarily biomass and heat (through e.g. district heating). Direct CO2 emissions are calculated using specific CO2 emission factors for each of the fossil fuels. Electricity and “others” are not associated with any direct CO2 emissions. In the model indirect emissions from electricity used within industry are estimated, but presented separately.

The development of energy prices for these energy carriers in the Pathway project have been described in general terms above. Common price developments for world market energy carriers (oil, coal and natural gas), based on EE&TT, are used for all pathways, while costs of CO2 and green certificates vary between pathways. On the basis of world market fuel prices and assumed energy and climate policy mix, total prices of fuels and electricity are estimated using the scenario tool ENPAC [Axelsson and Harvey, 2010]. In the TD model, assumed values on energy price elasticities and AEEI constants are based partly on literature data and partly on regression analyses of historic time series data of energy per added value and energy prices in Europe. Consequently, future development of energy demand is, as generally in econometrically based studies, assumed to follow the historical pattern of autonomous change and reactions on relative price changes.

4.2 Model results

The top-down model has been used to model energy demand and CO2-emissions of the European industrial sector as a whole, based on the results of each sub-sector. The development has been modelled for the Baseline development and for the Policy and Market Pathways.
In Baseline, energy use in the entire sector (excluding refineries) increases from 3588 TWh to 4807 TWh, which is an increase by 34%. Since the increase in value added is assumed to be 111%, this implies a significant reduction of energy use per value added (see Figure 2). Thus, in economic aggregated terms, the energy efficiency of the industry increases substantially.

In Baseline, energy prices, according to the projections in EE&TT and in the absence of CO₂ reduction policies, increase only slowly. The price of crude oil, for instance, is assumed to remain at a price level around $60/barrel from 2020 and onwards. Consequently, the change in specific energy use per value added depends, in the Baseline scenario, primarily on the representation of price-independent energy efficiency improvements in the model. The difference between Baseline and constant energy per value added is thus assumed to depend primarily on structural changes and on energy efficiency improvements related to learning and gradual technological development (i.e. without major technological breakthroughs).

Figure 2. Development of energy use in industry 2000-2050 for Baseline and the two pathways, Policy and Market. To illustrate the reduction of energy use included in baseline, the figure also includes development of industrial energy demand if the specific energy use (kWh/€) would remain constant throughout the entire period.
The impact of AEEI in the model does not change between scenarios. The difference between Baseline and the policy pathways (Policy and Market) are, in the top-down modelling results, thus dependent on price changes only. The differences in result between the Policy and Market pathways are small, since the price differences between them are small.

In the Market Pathway, as an example, the cost of CO₂ increases gradually from 20 €/ton in 2010 to 80 €/ton in 2050. The CO₂ cost impacts both the price level of energy in general and the relative price change between more and less CO₂ intensive energy carriers. As a result, total energy use decreases substantially compared to Baseline development and CO₂ emissions decrease even further (17% and 35% in 2050, respectively). The changes can be assumed to consist primarily of direct measures for improving energy efficiency and fuel substitution, mostly towards less CO₂-intensive fossil fuels.

In the Policy Pathway, policies directed towards reaching targets for energy efficiency improvements and renewable energy are assumed to include also regulatory (i.e. not price-based) policy instruments, such as sharpening of performance standards and stipulation of use of specific technologies. Effects of this type of policies are not taken into account in the applications of the TD model, since the AEEI constants are assumed to be the same between scenarios.
In this chapter we present results for the different industry sectors. The first sub-chapter include some general measures that can be applied at various degrees for all sectors. It is followed by sector specific sub-chapters, all including three parts:

1. Results from the top-down model.
2. A review of bottom-up studies of specific measures for reducing emissions, included in the Pathway project and elsewhere.
3. A qualitative discussion and quantitative estimate of relevant adjustments of results from the top-down model, based on sector specific bottom-up analyses.

Mineral oil refineries are not included in the top-down model and thus reviewed from a bottom-up perspective only.

5.1 General measures

The focus of the industrial analyses within the Pathway project has been on energy-intensive industries and thus on process specific energy use. This synthesis includes also general measures for energy efficiency improvements and CO₂ reduction. These measures are especially important in non-energy-intensive sub-sectors, which primarily use energy for heating of buildings and in help systems. This part of the synthesis is, however, less thorough and based on a relatively limited literature study.

The following two Pathway sub-projects have their focus on a specific type of measure and concern therefore more than one industrial sub-sector:

- Analysis of the potentials for increasing the use of biomass for process heat in the German industry [Göckeler, 2007]. The analysis includes all industrial sub-sectors.
- Analysis of the opportunities for CCS in European heavy industries, with a special focus on iron and steel production, cement industry, and mineral oil refineries [Rootzén et al, 2009].

The possibility to use biomass for heat production in industry has been studied for the German industry. German industry structure is, however, very similar to the average of the entire European industry. The result is therefore relevant for the European industry as a whole. The potential was estimated based on the demand for heat at different temperature levels. All heat demand below 400°C was assumed to be possible to generate with biomass. If the result from the German industry is applied on the EU industry the potential use of biomass would then be 1570 TWh. Heat use between 100°C and 400°C can in the same way be estimated to 840 TWh. Heat at temperatures below 100°C could potentially be supplied through increased process integration or by district heating systems. No economical restrictions were considered. A detailed study of the dairy industry show that the full
potential is unlikely to be implemented since there is a high capital cost to change fuel, and the fossil fuel cost is acceptable. Sector specific adjustments of the calculations are presented for the different industry sectors.

The potential for CCS in the industrial sector has been studied in Rootzén et al [2009]. Emphasis is in this study placed on three branches of industry with promising prospects for CCS: mineral oil refineries, production of iron and steel, and cement. Potential capture sources have been identified and the potential for CO₂ capture has been estimated based on branch and plant specific conditions. The geographical distribution of point sources, the occurrence of potential capture clusters and their location in relation to suitable storage sites have been assessed through geospatial analysis.

To identify regions with favourable clustering of CO₂ sources, emissions from 871 large stationary point sources have been summarized, depending on geographical location. According to this study, realizing the full potential of the CO₂ capture technologies considered would lead to avoidance of 60-75% (270-330 Mt CO₂/year) of the emissions from large industry point sources.

Apart from these two studies, estimates for general measures for increasing energy efficiency, or reducing primary energy consumption or CO₂ emissions have been based on data in the literature on sector-wide technologies. To a large extent data are based on Worrell et al [2009] and the references used there. Such measures, which can be applied to all sectors, include:

- More efficient steam generation,
- Energy recovery (heat, power and fuel recovery) and process integration,
- Energy efficiency improvements in electricity use,
- Co-generation of heat and power, and
- Co-siting, material and energy transfer between different companies at the same site.

It has been estimated that steam generation consumes about 15% of global final industrial energy use. The efficiency of steam boilers may, compared to the current average, be improved with a few percentages. Energy recovery and process integration include both gradual improvements in existing equipment and more radical changes, which require substantial investments. Process integration is mostly discussed for process industries, but is, at different scales, relevant for all types of industries. General potential for cost efficient process integration leading to efficiency improvements in heat use is typically estimated to 5-40% [Worrell et al, 2009].

Increasing the energy efficiency in electricity use implies to a large extent more efficient motor driven systems. 65% of industrial electricity use is used for motor driven systems, including for instance pumps, fans and compressed air systems [Worrell et al, 2009]. For the industry in EU-25 implementing more efficient motor driven systems could give a 30% reduction in electricity use. The total savings would be 200 TWh, calculated on the electricity use in 2000. Since the use of electricity is expected to increase, the same relative reduction of the electricity demand predicted in 2050 would lead to total savings of 350 TWh. The distribution of electricity use in motor driven systems, between the industrial sub-sectors is presented in a European study [EU-SAVE, 2000]. In the following sections, the resulting potential is discussed for each industrial sub-sector.
The remaining 35% of electricity use is divided between primarily process specific electricity use (e.g. electrolysis), electricity use for heating purposes, and lighting. Electricity use for lighting are significant in some sub-sectors, such as manufacturing of equipment goods. New lighting systems have in many studies been identified as an area with large potentials for efficiency improvements. Best available techniques have been estimated to reduce energy use in current lighting systems with 30-50% and in the perspective to 2050 a 50% reduction should thus be realistic [ENE BREF, 2009].

In many cases electricity and heat use are linked together in complex systems. As an example, optimization of ventilation systems leads to reductions both in electricity use and heat demand. However, at an aggregate level, both potentials are included in the aggregate estimates for motor system and energy recovery above.

The potential for industrial co-generation is discussed specifically for some industrial sub-sectors below. In aggregate, the potential for electricity production through industrial co-generation in Europe has been estimated to about 400 TWh per year. Current production is about 200 TWh per year.

The potential for efficiency improvements, and/or CO$_2$ reductions, through co-siting, is highly dependent on site-specific conditions and difficult to estimate on an aggregate level. In some cases, the potential may be very high. On average, the practical potential have, however, been estimated to about 5% [Worrell et al, 2009].

### 5.2 Primary metals

The primary metals sector includes the two sub-sectors iron and steel production and non-ferrous metals production. The iron and steel industry use more than 80% of total energy use in the Primary metal sector (95% of total coal use and 60% of electricity use). Thus, the opportunities for reducing CO$_2$ emissions are largest in the iron and steel industry.

An initiative by European steel producers to develop ultra low CO$_2$ steel production (ULCOS) has presented a study of the potential developments of the iron and steel sector. In this study, it is pointed out that significant reductions of CO$_2$ emissions have been made over the last 40 years and that mere process development cannot contribute to further large reductions. Three areas of development to reduce CO$_2$ emissions are identified:

- Decarbonizing, by shifting from coal to natural gas and electricity
- Implementation of carbon capture and storage, integrated with the industrial plants,
- Use of biomass, to partly replace coke and coal.

Development of new materials is also expected to contribute in achieving reductions of CO$_2$ emissions. Thinner material can give lighter-weight products and will reduce the energy required in several applications. Savings are made both in the production and transportation of goods.

New materials can also be part of other energy efficiency solutions such as material made to resist higher temperatures that will enable higher steam pressure and temperature in steam power plants and thus increase the efficiency in electricity generation plants [Gielen et al, 2008].
5.2.1 Primary metals - Results from top-down model

Compared to Baseline, model results show that energy demand in the primary metals sector will be about 250 and 300 TWh (or about 30%) lower in 2050 in the Policy and Market pathways, respectively. The relative reductions of CO\textsubscript{2} emissions are more or less the same. Thus, we see mainly a reduction in energy demand and only very small effects from fuel shifts. During the same period the production volume, in terms of value added is assumed to increase with 71% (see Table 1). Part of this increase in production volume can be explained by product development towards new, thinner materials, increasing the value-added, without a corresponding increase in physical output of material.

![Figure 4. Result from the TD-model - energy supply for the Primary metal industry sector in 2000 and in 2050 for the baseline and the two pathways, Policy and Market](image)

![Figure 5. Development of CO\textsubscript{2} emissions in the Primary metal industry 2000-2050 according to the TD-model and after adjustments (dotted lines).](image)
In line with the discussion in section 4.2, the changes between baseline development and respective pathway can mainly be interpreted as price-induced energy efficiency improvements.

5.2.2 Primary Metals - Bottom-up analyses

Within the Pathway project, the iron and steel industry has been studied thoroughly. Related Pathway sub-projects include:

- Sub-sector analysis of the iron and steel industry, based on a capital vintage model [Thorén and Wirsenius 2010].

- Analysis of the opportunities for CCS in the iron and steel industry, as part of the assessment of CCS in European heavy industries [Rootzén et al, 2009].

- Two different studies that explore the possibilities to replace fossil fuels with bioenergy [Göckeler, 2007, Johansson et al, 2009].

Overall sub-sector analysis

A capital vintage model for the iron and steel industry in EU15 has been developed and used for a sub-sector systems analysis [Torén and Wirsenius, 2010]. The model is based on a capital vintage model first developed for the US iron and steel industry [Ruth, 2000], which has been adapted to European conditions. In the model, an increasing production volume, together with the phase-out of existing capital stock, drives the demand for new, more energy efficient, capital stock. Production is assumed to be based on an increasing share of secondary steel and, as a consequence, an increasing share of electric arc furnace (EAF) and decreasing energy use. Thus, the sector analysis includes both structural change, in terms of increasing use of secondary steel, and improvements in energy efficiency. It also includes the consequences in terms of fuel shifts from these changes. The evaluation is made for several scenarios until 2030. In the calculations of total CO₂ emissions, indirect emissions from electricity use are included (gradually shifting towards less CO₂-intensive electricity production).

The result of the study is that energy efficiency improvements in the blast furnace, structural change and decreasing CO₂ emissions from electricity use could result in emission cuts of 20-40% until 2030 [Torén and Wirsenius, 2010]. The electricity demand would increase by 30%. The use of natural gas would more than triple in the Policy and Market scenario, where it will replace more coal than in the Baseline scenario and all oil. These shifts in energy carriers are not seen in the top-down modelling results.

To support the result of the capital vintage study a thorough literature study was conducted to point at actual measures that can be implemented to reach the energy efficiency development shown in the model. Some of the measures are already partly implemented, which reduce the potential of further reduction. The measures listed are primarily linked to blast furnace steel production and include:

- Improve energy efficiency by using high grade ore.

- Hot stove optimization for heating the blast in the blast furnace process.

- Energy recovery from top gas pressure, by using the pressure drop between the hot top gas and the surroundings in an expansion turbine and generate electricity.

- Blast furnace gas recovery, through Top Gas Recycling (TGR), using hydrogen and
CO in the gas as fuel (especially interesting in combination with CCS, see below).

- Basic oxygen furnace gas recovery.
- Direct injection of reducing agents, exchanging coke for alternative, less CO₂-intensive fuels.
- Near-net-shape casting.

**Structural changes**
The only structural change taken into account here is the shift from primary ore to scrap metal. The shift could result in an increase in the share of steel produced in electric arc processing from 42% in 2005 to 56% in 2030 [EU -EE&TT, 2007]. As a consequence, total energy use and direct CO₂ emissions would decrease strongly while electricity use would increase.

**Energy efficiency measures**
The results from the capital vintage model can be translated into energy efficiency improvements corresponding to about 80 TWh per year in the year 2030. The combined potential of the identified measures for energy efficiency improvements in the literature study is, based on current production level, substantially larger (about 150 TWh). The potential is relevant also in the long term, since blast furnace steel production in Europe here is expected to level off. The most important specific measure would be increasing the recovery of blast furnace gas. Further energy efficiency improvements might be possible, but they would be the result of more radical technology shifts.

Besides iron and steel, aluminum production is responsible for a large share of the energy use in this sector. The average energy use per ton aluminum in Europe is higher than world average. Replacement of smelters in aluminum industry will reduce the amount of energy required [IEA, 2009]. Inert anodes could reduce electricity demand with 10-20% compared to today’s best.

In addition to the process specific measures discussed above, general efficiency improvements are expected to take place also in the primary metals sector. One of the most important areas would be shifting towards energy efficient motor systems. The potential for reducing electricity use in iron and steel production has been estimated to 44 TWh [EU-SAVE, 2000].

**Fuel substitution**
The potential for using biomass in the primary metal sector is limited due to the high temperatures required. In the study based on German industry, only 12% of the heat demand is below 400°C, half of which is below 100°C [Göckeler, 2007]. Maximum CO₂ reduction would be about 20 Mton/yr.

A more detailed analysis of the potential for replacing fossil fuels with biomass in Swedish primary metals industry shows that about 30% of the coke could be replaced with biomass based charcoal in the blast furnace process.

| Table 2a. Reduction in energy use and CO₂ emissions from top-down model |
|---------------------------------|-----------------|-----------------|
|                                 | Energy [TWh]    | Direct CO₂ emissions [Mton/yr] |
|                                 | Policy/Market   | Policy           | Market           |
| Reduction compared to Baseline  | -264/-308       | -60              | -72              |

24
### Table 2b. Reduction in energy use and CO₂ emissions from bottom-up estimates of the potential of specific measures (potentials are not additive) - Primary metal industry

<table>
<thead>
<tr>
<th></th>
<th>Energy [TWh]</th>
<th>Direct CO₂ emissions [Mton/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>STRUCTURAL CHANGE</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total energy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity</td>
<td>-100</td>
<td>+ 40</td>
</tr>
<tr>
<td>Biomass</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂ change</td>
<td>-30</td>
<td></td>
</tr>
<tr>
<td><strong>ENERGY EFFICIENCY IMPROVEMENTS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total result from CV model³</td>
<td>-80</td>
<td>-10</td>
</tr>
<tr>
<td>Using high grade ore²</td>
<td>↓</td>
<td>-10</td>
</tr>
<tr>
<td>Hot stove optimization²</td>
<td>-17</td>
<td></td>
</tr>
<tr>
<td>Top gas pressure energy recovery²</td>
<td>-13</td>
<td>-13</td>
</tr>
<tr>
<td>Blast furnace gas recovery (replace NG)²</td>
<td>-100</td>
<td>-20</td>
</tr>
<tr>
<td>Basic oxygen furnace gas recovery²</td>
<td>-33</td>
<td></td>
</tr>
<tr>
<td>Energy efficient motor systems¹</td>
<td>-44</td>
<td>-44</td>
</tr>
<tr>
<td>District heat used for heat below 100 °C¹ (potential 35 TWh)</td>
<td>↓</td>
<td></td>
</tr>
<tr>
<td><strong>FUEL SUBSTITUTION</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Charcoal instead of coke in the blast furnace process¹ or</td>
<td>↑</td>
<td>57</td>
</tr>
<tr>
<td>Direct injection of reducing agents¹</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Coal instead of coke or</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- SNG instead of coke</td>
<td>↑</td>
<td>100</td>
</tr>
<tr>
<td>Replace all oil with NG³</td>
<td>0</td>
<td>-15</td>
</tr>
<tr>
<td>12 % of energy use is heat below 400 °C, replace with biofuel¹</td>
<td>0</td>
<td>+70</td>
</tr>
<tr>
<td><strong>CCS</strong></td>
<td></td>
<td>-106</td>
</tr>
<tr>
<td><strong>FUTURE TECHNOLOGY LEAPS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrolysis production processes</td>
<td>↓</td>
<td>↑</td>
</tr>
<tr>
<td>Near-net-shape casting</td>
<td>↓</td>
<td></td>
</tr>
<tr>
<td>New aluminium process²</td>
<td>-15</td>
<td>-15</td>
</tr>
</tbody>
</table>

¹ Estimated for the year 2050, based on pathway development ² Based on current production ³ Based on the results of the CV model for the year 2030. (↓ = decrease, quantity unknown, ↑ = increase, quantity unknown).
[Johansson et al, 2009]. On the European level this would translate to a CO$_2$ reduction of 15-20 Mt/yr. Since charcoal can be used for temperatures above 400°C, this is an additional potential for biomass use.

Increasing the direct injection of reducing agents, exchanging coke for pulverized coal or less CO$_2$-intensive fuels, such as natural gas, biomass or synthetic natural gas (SNG) would also reduce CO$_2$-emissions. As an example, complete substitution of current use of pulverized coal and fuel oil for natural gas or biomass would reduce specific emissions in EU-15 steel production by 10-15% [Croezen and Korteland, 2010]. With further refining of biomass into SNG, biomass could play a role also in natural-gas-based reduction processes.

**CCS**

In the iron and steel industry the blast furnace is the largest source for CO$_2$ emissions in integrated steel plants, being responsible for 65% of the emissions at the plant. If conventional blast furnaces are replaced with Top Gas Recycling the potential for CCS would be about 106 Mt CO$_2$/yr, based on current production levels [Rootzén et al 2009]. The potential in 2050 depends on structural change to that time.

**Future technology leaps**

In iron and steel production technological leaps may impact total energy use substantially. Firstly, iron production based on electrolysis production processes, similar to aluminium smelting, would increase the shift from coal to electricity use and give reductions in CO$_2$ emissions, depending on how electricity is produced [ULCOS, 2010]. Another completely new process for iron casting, called near net-shape casting has the potential to reduce energy use for that process radically (-90% of energy use) [IEA, 2008]. The potential for implementing such a technology shift is, however, uncertain.

New processes for aluminium production include so called kaolinite reduction. This would be an alternative to the present route for primary aluminium production, which could reduce energy demand with up to 35% [IEA, 2009].

**5.2.3 Primary metals - Realisation of potentials in the pathways**

For the primary metals sector, several quantitative adaptations of the top-down modelling result are made. The adjustments result in potentially low total direct emissions from the sub-sector due to the combined effect of electrification, increased biomass use and CCS (see Figure 5).

A more detailed sub-sector analysis than provided by the top-down model shows that a continued shift towards increasing scrap metal recovery would lead to both more efficient energy use and a shift from coal and coke towards natural gas and electricity. This structural change has been an ongoing development and can be assumed to be accounted for in the top-down model through the AEEI constant, in terms of total energy use. According to modelling results, the directly linked effect on the composition of energy carriers is, however, not included. The development should therefore be adapted in both the Policy and Market pathways.

Apart from this structurally induced change, the combined potential for technically feasible energy efficiency improvements listed above adds up to about 200 TWh/yr, which is clearly lower than the reduction in energy use between baseline and respective pathway in the top-down modelling results. Even though the potential is uncertain and depend on the
development of total production volume, it is therefore reasonable to adapt total energy use slightly upwards for the Market pathway. In the Policy pathway, specific energy efficiency policies are assumed to be implemented, that increase the possibilities to reach large reductions in energy use.

As argued in section 3.2, the potentials for CCS and fuel shift towards biomass represent new directions for this industrial sub-sector, which can be assumed not to be accounted for in the top-down modelling approach. Therefore, implementation would impact energy use and CO₂ emissions compared to top-down modelling results. However, due to the assumed structural change, including electrification and increasing shares of natural gas, the technical potentials listed above have been substantially reduced.

5.3 Chemicals

Chemicals cover many different products and the variation in energy input per value added is large. As an example, pharmaceuticals and cosmetics make up 50% of the value added, but accounts for only 10% of total energy used. Structural change towards more valued products, that could reduce the energy intensity of the sector substantially, may thus be anticipated.

The specific GHG emissions per value added in the EU Chemical industry (including pharmaceuticals) have been reduced with more than 50% between 1990 and 2006. Total energy demand has been reduced with more than 20% during the same period. This indicates that energy efficiency measures have been implemented [CEFIC, 2010].

Most of the production is today based on fossil hydrocarbons, but many of the chemicals can in principle also be produced using bio-based feedstocks. CO₂ emissions from the chemical sector can also be reduced by reuse, recycling and energy recovery [Gielen et al, 2008].

5.3.1 Chemicals - Results from top-down model

Compared to Baseline, model results show that the energy demand in the chemical sector will be about 20% lower in 2050 in both the Policy

Figure 6. Result from the TD-model - energy supply for the baseline and the two pathways, Policy and Market.
and Market pathways. The relative reductions of CO₂ emissions are more or less the same, and also here the effects from fuel shifts are small. For the chemical sector, the assumed growth in production volume is, as value added, large (143%), and as a result total energy use increases, compared to the year 2000 (see Table 1 and Figure 6).

5.3.2 Chemicals - Bottom-up analyses
The chemical sector has not been included in pathway studies except for the general analysis of the potential use of biomass in industry [Göckeler, 2007]. Since the chemical sector is an energy intensive sector, there are however other sources that list measures for CO₂ mitigation and possible energy efficiency improvements.

Structural changes
Structural change in the chemicals sector includes increasing share of plastic material recycling. This would reduce the raw material input (oil) and energy use in the production processes. Today, most collected plastic is used for energy recovery and not for material recycling.

Another, more fundamental, structural change would be a shift towards biomass feedstock. It has been estimated that bio-based plastics could, from a purely technical point of view, replace around 80% of petrochemical-based plastics [IEA 2009]. The use of biomass for polymers would also eliminate CO₂ emissions from the end product. End product emissions are not included in statistics for industrial emissions, and only partly in other sectors (primarily from waste incineration).

Biomass as feedstock in the chemical industry can be implemented in four ways:
- Using natural occurring polymers.
- Thermochemical conversion of biomass (pyrolysis or gasification).
- Green biotechnology – using genetically modified crop.
- White biotechnology – using biological processes (fermentation).

A general trend that has been identified for the sector is an increasing share of electricity in total energy use. Structural product changes are expected to increase both the use of electric motors and electro-chemical processes [IEA 2009].

Energy efficiency measures
As mentioned above, the chemical sector is diverse and so are its production processes. This makes an overall sector analysis of energy efficiency improvements difficult. However, some specific unit operations that are widely used in the industry can be identified.

One of these unit operations is separation, which also requires large quantities of energy. In literature it is estimated that membranes and other new separation technologies can save approximately 5% of all energy used in the Chemical sector [IEA 2009]. Other promising areas include improving catalyst performance in order to increase the efficiency of chemical reactions, which could reduce specific energy use with 6-10% [IEA 2009].

The chemical industry, especially the basic petrochemical industry, is an energy-intensive process industry, with many heat based processes and often with available heat surplus. Consequently, there are opportunities for optimising energy use within and between processes through process integration. The potential for improving energy efficiency through process integration has been estimated
to about 5-10% of the energy used in the sector [IEA 2009]. The heat surplus is today only rarely utilized for district heating. Also with an integrated process, the potential for utilising heat surplus for district heating should be substantial, but is difficult to quantify.

Other measures that are difficult to quantify include combined heat and power generation (CHP). According to IEA, there is, however, still large unused potential for CHP in the chemical industry [IEA 2009].

70% of energy use in the chemical sector is used for production of olefins, ammonia and methanol, which make the production processes for these products especially interesting. Several measures for these processes are described in literature. Two specific examples, representing improvements in separation processes and process integration, are:

- Development of a new solvent for CO\textsubscript{2} separation in ammonia production.
- Integration of gas turbines with cracking heaters in olefin processes.

General energy efficiency measures such as energy efficient motor systems hold a potential for reducing energy use also in the chemical sector. Estimates of the potential are based on overall data for industry [EU-SAVE 2000].

**Fuel substitution**

Energy use in the chemical industry is to a large extent based on the raw materials used. Structural change towards biomass for feedstock would, therefore, most likely increase also the share of bioenergy in the sector. This structurally imposed fuel substitution is taken into account under “structural change”, above. In German chemical industry 50% of the heat demand is estimated to be at a temperature below 400°C, which in principal means it could be produced with biofuel [Göckeler, 2007]. The potential reduction of CO\textsubscript{2} emissions has been estimated to be about 50 Mt/yr.

**CCS**

The large bulk products, olefins (ethylene and propylene), methanol and ammonia are large point source emitters of CO\textsubscript{2}. This makes the production sites interesting for CCS. The chemical industry is not included in the Pathway study of CCS in industry. However, the potential and cost for CCS at an ethylene plant has been estimated in the Skagerrak project [Tel-Tek, 2008]. Based on these figures a very rough estimate for a European potential can be made.

As part of conventional production of ammonia, one of the process streams consists of separated CO\textsubscript{2}. This would, of course, be a major advantage when it comes to CCS. Currently, this CO\textsubscript{2} is in general used for urea production, but could technically also be compressed and stored at an economically interesting cost.

**Future technology leaps**

Future technology leaps in the chemical industry includes partly new radical process design ideas in the petrochemical industry, so called process intensification, partly a shift towards biological processing in general. Process intensification has been estimated to have a potential to reduce the energy required with 20% in 40 years perspective, which on the European level corresponds to about 15-20 TWh [IEA, 2009]. A technology shift towards biological processing could dramatically impact specific energy use for producing chemicals, but the potential is difficult to quantify [Worrell et al, 2009].
Table 3a. Reduction in energy use and CO₂ emissions from top-down model - Chemical industry.

<table>
<thead>
<tr>
<th>Energy [TWh]</th>
<th>Direct CO₂ emissions [Mton/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Policy/Market</td>
<td>Policy/Market</td>
</tr>
<tr>
<td>Reduction compared to Baseline</td>
<td>-202/-236</td>
</tr>
</tbody>
</table>

Table 3b. Reduction in energy use and CO₂ emissions bottom-up estimates of the potential of specific measures - Chemical industry

<table>
<thead>
<tr>
<th></th>
<th>Energy [TWh]</th>
<th>Direct CO₂ emissions [Mton/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>STRUCTURAL CHANGES</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total energy</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material recycling</td>
<td>↓</td>
<td>↓</td>
</tr>
<tr>
<td>Bio based polymers</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td><strong>ENERGY EFFICIENCY IMPROVEMENTS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Membranes and other separation technologies¹</td>
<td>-49</td>
<td>-6</td>
</tr>
<tr>
<td>Process integration, 10 % reduction¹</td>
<td>-100</td>
<td>-12</td>
</tr>
<tr>
<td>Process integration GT in cracker heaters – ethylene production²</td>
<td>-15</td>
<td>↑</td>
</tr>
<tr>
<td>Catalyst improvements, 10 % reduction¹</td>
<td>-100</td>
<td>-12</td>
</tr>
<tr>
<td>New solvent for CO₂ separation in ammonia process²</td>
<td>-5</td>
<td></td>
</tr>
<tr>
<td>Use of CHP</td>
<td>↑</td>
<td>↓</td>
</tr>
<tr>
<td>More efficient steam generation</td>
<td>↓</td>
<td>↓</td>
</tr>
<tr>
<td>Energy efficient motor systems¹</td>
<td>-85</td>
<td>-85</td>
</tr>
<tr>
<td><strong>FUEL SUBSTITUTION</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>43 % of energy use is heat is below 400 °C, replace with biofuel¹</td>
<td>0</td>
<td>-60</td>
</tr>
</tbody>
</table>

| **CCS**                              |              |                                |
| CCS Ethylene plants²                 | ↑            | -16                            |
| CCS Ammonia production²              | ↑            | -10                            |

| **FUTURE TECHNOLOGY LEAPS**          |              |                                |
| Process intensification – ethylene production² | -20 | | -4 |
| Biotechnology processing             | ↓            | ↓                              |

¹ Estimated for the year 2050, based on pathway development ² Based on current production. (↓ = decrease, quantity unknown, ↑ = increase, quantity unknown).
5.3.3 Chemicals - Realisation of potentials in the pathways

For the chemicals sector, no sector specific bottom-up studies have been included in the Pathway project. Literature suggests, however, several quantitative adaptations of the top-down modelling result.

The potential for structural change in the chemical sector, leading to decreasing specific energy use, is large. However, this development seems to be well mirrored in the top-down modelling results. Specific energy use (per value-added) decreases in the baseline scenario with one-third between the years 2000 and 2050. The effects from this development on the types of energy carriers used is unknown, but in the absence of CO2 reduction targets (as in the baseline development) fuel substitution would most likely be small.

The total potential for energy efficiency improvements, based on available literature, is apparently large, well corresponding to the decrease in energy use resulting from the top-down model. In the Policy pathway, with specific policies aiming at increasing the energy efficiency on the demand side, it is therefore realistic to assume a higher implementation of energy efficiency improvements than in the Market Pathway. Such a development is not accounted for in the top-down model, since the difference between the pathways and baseline is purely price-driven.

As for the other industrial sectors, the potentials for CCS and fuel shift towards biomass need to be accounted for beyond the top-down modelling results. Fuel substitution for biomass could be accomplished via direct fuel substitution or via changes in raw material and feedstock, which in turn may be supported by newly developed biotechnology processing.

5.4 Non-metallic minerals

The non-metallic mineral sector consumed 11% of the energy used in the industry sector (including refineries) in 2005. The energy is mainly used in high temperature thermal processing. Specific energy use has been reduced by 30% the last 20 years by moving towards larger production units and also adopting the dry process of cement manufacture. The cement industry is the most energy using sub-sector, using approximately 50% of the energy. In addition, the cement production process leads to non-energy related CO2 emissions, increasing total emissions from the sector by about 55%.

There is still room for efficiency gains by converting the remaining wet and semi-wet processes (corresponding to about 10% of total production) to dry process and to adopt best available technology [EU – EE&TT 2007].

5.4.1 Non-metallic minerals - Results from TD-model

Compared to Baseline, model results show that energy demand in the non-metallic sector will be about 150 and 180 TWh (or 25-30%) lower in 2050 in the Policy and Market pathways, respectively. Furthermore, model results show a clear shift from coal to natural gas in the sector. Total CO2 emissions from the sector include also non-energy related emissions from the cement process. These are assumed to change proportionately to energy use (and not to the production volume).
5.4.2 Non-metallic minerals - Bottom-up analyses

Within the Pathway project, the non-metallic industry has been studied in a number of studies. Related Pathway sub-projects include:

- The cement industry is included in the assessment of CCS in heavy industry [Rootzén et al, 2009]. The study includes two alternative routes for CCS and their capture potential.

- A literature review of the cement industry was made to find options for CO₂ mitigation measures. Mitigation technologies include equal parts of energy efficiency improvements, reduction of clinker content of cement and fuel substitution [Cortés, 2009].

- Biomass use in the non-metallic industry is included in the work on potentials for biomass based on temperature requirements [Göckeler, 2007].

Structural changes

Structural change in the cement industry includes primarily a reduction of clinker production. This is possible by replacing clinker with other materials, such as fly ash, volcano ash, ground limestone or broken glass. This is already done to some extent, and the additional potential is 7-9% expressed in CO₂ emissions reduction [Cortés, 2009].

Energy efficiency measures

Implementation of BAT technology in the European cement industry would reduce CO₂ emissions with 8% and energy demand with 17-20% [Cortés, 2009]. Such a reduction has been estimated to reduce energy use with 50 TWh/yr and CO₂ emissions with 20 Mt/yr. In addition, a process integration solution where clinker and energy is produced in one plant could reduce CO₂ emissions with 5-10%.

Excess heat can be recovered and used for low temperature electricity production or district heating.

Much of the electricity used in the sector is used for motor systems and by using more energy efficient motor systems the electricity use could be reduced with about 35 TWh [EU-SAVE 2000].
**Fuel substitution**
The possibilities to replace fossil fuels with biomass are in this sector small. Assuming that only fuel is used for heat production, 10% of the fossil fuel would be possible to replace [Göckeler, 2007]. In the cement kilns it is also possible to use natural gas or low quality fuel such as waste, which would reduce the use of primary energy and may reduce the CO2 emissions, depending on the type of waste used. It would be technologically possible with a complete fuel switch to a combination of natural gas and biomass. This would translate to reduction of specific CO2 emissions by about 25% per tonne clinker, compared to the currently best performing plants [Croezen and Korteland, 2010].

**CCS**
The potential for CCS in non-metallic industry depends on the process solution. Two interesting options are post combustion capture of flue gases and oxyfuel operation in cement plant precalciners. The capture of CO2 would be 107 or 67 Mt CO2/yr, depending on process and based on current production levels [Rootzén et al, 2009]. The amount of energy required for CCS would, according to the IEA report that the above CO2 reduction potentials are based on, be substantial, especially for the post combustion process [IEA GHG, 2008] (see Table 4). The additional energy required for post combustion would generate CO2 as well (depending on fuel). As a result, the amount of captured CO2 would be about 45% larger than the reduction in CO2 emissions from the plant.

**Future technology leaps**
Development of new materials with new additives can reduce energy use and CO2 emissions further. One example is the development of alternative clinker types with lower CO2-emissions, such as magnesium based clinker [Croezen and Korteland, 2010].
### Table 4a. Reduction in energy use and CO₂ emissions from top-down model - Non-metallic industry

<table>
<thead>
<tr>
<th>Policy/Market</th>
<th>Energy [TWh]</th>
<th>Direct CO₂ emissions [Mton/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduction compared to Baseline</td>
<td>-152/-182</td>
<td>-68/-90</td>
</tr>
</tbody>
</table>

### Table 4b. Reduction in energy use and CO₂ emissions from top-down model and bottom-up estimates of the potential of specific measures - Non-metallic industry

<table>
<thead>
<tr>
<th>Energy [TWh]</th>
<th>Direct CO₂ emissions [Mton/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Policy/Market</td>
<td>---</td>
</tr>
</tbody>
</table>

#### STRUCTURAL CHANGES

<table>
<thead>
<tr>
<th>Total energy</th>
<th>Electricity</th>
<th>Biomass</th>
<th>CO₂ change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blended cement, reducing clinker production²</td>
<td>-25</td>
<td></td>
<td>-25</td>
</tr>
</tbody>
</table>

#### ENERGY EFFICIENCY IMPROVEMENTS

<table>
<thead>
<tr>
<th>Total energy</th>
<th>Electricity</th>
<th>Biomass</th>
<th>CO₂ change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Implementing BAT¹</td>
<td>-50</td>
<td></td>
<td>-20</td>
</tr>
<tr>
<td>Energy recovery - district heat delivery or electricity production²</td>
<td>-5</td>
<td>↓</td>
<td>-10</td>
</tr>
<tr>
<td>Energy efficient motor systems¹</td>
<td>-35</td>
<td>-35</td>
<td></td>
</tr>
</tbody>
</table>

#### FUEL SUBSTITUTION

<table>
<thead>
<tr>
<th>Total energy</th>
<th>Electricity</th>
<th>Biomass</th>
<th>CO₂ change</th>
</tr>
</thead>
<tbody>
<tr>
<td>10% of energy is heat below 400°C, replace with biofuel¹</td>
<td>0</td>
<td>+35</td>
<td>-10</td>
</tr>
<tr>
<td>Using waste as fuel¹</td>
<td></td>
<td></td>
<td>-20</td>
</tr>
</tbody>
</table>

#### CCS

<table>
<thead>
<tr>
<th>Total energy</th>
<th>Electricity</th>
<th>Biomass</th>
<th>CO₂ change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assessment of CCS in Non-metallic industry²</td>
<td>+357</td>
<td>-20</td>
<td>-107</td>
</tr>
<tr>
<td>Assessment of CCS in Non-metallic industry²</td>
<td>+16</td>
<td>+14</td>
<td>-67</td>
</tr>
</tbody>
</table>

#### FUTURE TECHNOLOGY LEAPS

<table>
<thead>
<tr>
<th>Total energy</th>
<th>Electricity</th>
<th>Biomass</th>
<th>CO₂ change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hybrid energy and cement plant</td>
<td>↓</td>
<td>↑</td>
<td>-30</td>
</tr>
<tr>
<td>Development of new materials with new additives²</td>
<td></td>
<td></td>
<td>↓ ↓</td>
</tr>
</tbody>
</table>

¹ Estimated for the year 2050, based on pathway development ² Based on current production. (↓ = decrease, quantity unknown, ↑ = increase, quantity unknown).
5.4.3 Non metallic minerals - Realisation of potentials in the pathways

In the non metallic minerals sector, estimated potentials for both structural change, leading to decreasing specific energy use, and energy efficiency improvements are relatively moderate, compared to the results from the top-down model. Given the increase in production volume assumed in the modelling study, the sector would need to undergo a major development to reach the energy and emission levels shown in the results. Total energy use is therefore adjusted upwards for both the Market and Policy pathways.

As in the sectors above, however, the potentials for CCS and fuel substitution for biofuel are assumed not to be accounted for in the top-down model. Increasing the share of bioenergy is primarily assumed to be relevant in the Policy Pathway. The estimate of CO$_2$ reduction through CCS in this sector is based on the oxyfuel process (alternative B), since the large additional energy demand connected to post combustion CCS is assumed to be prohibitive for its implementation.

5.5 Paper and printing

Energy use within the industrial sector Paper and printing is primarily connected with pulp and paper production. Printing accounts only for a few percentages of total energy use. Paper is produced from pulp or recycled paper. Paper production from pulp is considerably more energy intensive than production from recycled paper. In the Paper and printing sector, a large part of the energy used comes from the raw material (wood) and is thus biobased. The sector can contribute to decreasing emissions not only through decreasing use of fossil fuels, but also by increasing the efficiency of raw material use, thereby increasing deliveries of biomass based energy carriers.

Energy efficiency measures in the pulp industry, such as heat recovery and process control, have decreased specific energy use by 30% during the last decades. Further energy reductions can be made, but to reach very low levels heavy investments and new process technologies would be required.

5.5.1 Paper, printing - Results from TD-model

Compared to Baseline, model results show that energy demand in the paper, printing sector will be about 107 and 122 TWh (or 25%) lower in 2050 in the Policy and Market pathways, respectively. Furthermore, the top-down results indicate fuel shifting away from biomass (included in “others”). Total direct CO$_2$ emissions are in this sector low relative to total energy use. This depends on the large shares of biofuel, electricity and natural gas.
5.5.2 Paper and printing - Bottom-up analysis

The paper industry and primarily the energy demanding pulp industry is studied in several Pathway studies:

- The energy saving potential by process integration and new technology solutions and the best way to use the excess heat at the mill has been evaluated [Jönsson et al, 2008 and Jönsson et al, 2010a].
- Sub-sector analysis of the pulp and paper industry, based on a capital vintage model [Gasper et al, 2010].
- Assessment of CCS in the European pulp and paper industry has been made, based on case studies at plant level and detailed analysis of
integration possibilities to use excess heat for the CCS process [Jönsson et al 2010c].

- Biomass use in the paper industry is included in the work on potentials for biomass based on temperature requirements [Göckeler, 2007].

**Overall sub-sector analyses**

An economic evaluation of different options for using steam surplus in kraft pulp production is carried out in Jönsson et al [2008 and 2010a] by using a simulation model for industrial energy systems (reMIND). The model has been applied to a model mill with a production of 1000 ADt pulp/day, (ADt = Air dried tonnes), that represents an average Scandinavian pulp mill. The evaluation includes proven technologies such as electricity generation, bark export, district heat delivery, but also not yet implemented technologies such as lignin extraction, black liquor gasification and carbon, capture and storage.

Energy efficiency measures will generate a steam surplus that can be turned into products that can be exported. Assuming that these energy products will replace fossil energy in the surrounding energy system, global CO₂ emissions will be reduced. The evaluation is made for four different future energy market scenarios and for five different technology pathways. The result shows that new technology pathways will reduce CO₂ emissions more than the proven technologies, but the proven technology pathways are more robust to varying energy market prices. The technology pathway where steam surplus will be used for CCS will result in largest global CO₂ emissions reduction. However, it will only be economically interesting at a CO₂ cost above €45/ton.

In addition, a study of the pulp and paper industry analyses the effect of policy mechanisms on carbon emissions 1990-2020. The study is based on the same type of capital vintage model that is described in Section 5.2.2 and on recent data for the European pulp and paper industry. The policy mechanisms used are price signals to change fossil fuels to more biomass and investment policies to make it more economical to introduce energy efficiency measures, such as CHP and black liquor gasification. The result shows that price signals will give a larger reduction of CO₂, but that combined policies are most efficient [Gasper et al, 2010].

**Structural changes**

Maximum theoretical recovery rate of paper is 83%. In CEPI the recovery rate is 56%, which would mean that there is still room for improvement. Total energy use is reduced drastically when paper is made from recovered fibres, compared to pulp from virgin wood. However, the amount of surplus heat from pulp production is decreased as well.

**Energy efficiency measures**

If the data used in the overall sub-sector analysis described above are generalised for the entire kraft pulp industry in Europe, the energy efficiency potential can be estimated. Process integration only can, according to this study, reduce energy demand with 2.5-3 GJ/ADt. In a case when new technologies (i.e. new configuration of black liquor evaporation) are applied in addition to process integration, the specific energy reduction can be 5 GJ/ADt [Jönsson, 2010b]. Based on current total kraft pulp production of 25 Mt per year in Europe, this corresponds to savings of 20-35 TWh [CEPI 2009]. Process integration can be applied also in the production of semichemical and mechanical pulp. However, since heat use is much lower in these processes, the potential is relatively small.
Paper drying dominates the energy demand in paper making. About 25-30% of the energy used in the paper and printing industry sector is used for paper drying. Introducing new advanced drying technologies will reduce energy use or create excess energy in the drying section with 20-30% and will thus result in overall 5-10% savings [IEA 2009]. Papermaking requires lower enthalpy heat and if excess heat is available there is also a potential for savings by implementing process integration or heat pumps.

If the recovery boiler is replaced with a black liquor gasification unit the energy efficiency can increase. The gasified black liquor can be used for electricity generation or synthesis of fuels, that may have an indirect effect on global CO$_2$ emissions. Direct CO$_2$ emissions at the pulp mill will however not change, unless fossil fuel is replaced [Berglin 1996].

Electricity use in the pulp and paper industry is mainly related to different types of motor systems. By using more energy efficient motor systems electricity use could be reduced with about 50 TWh [EU-SAVE 2000].

**Fuel substitution**

Most of the heat used within paper and printing industry could be based on biomass, since temperature levels are relatively moderate [Göckeler, 2007]. Since biomass is the main raw material, much of this heat is already generated with bioenergy. Nevertheless, there is probably still a potential for replacing fossil fuel with biomass. In 2008 54.4% of the fuel used in the European Pulp and Paper industry was based on biomass [CEPI 2009]. If the full potential of biofuel replacement is carried out, CO$_2$ reduction would be approximately 9 Mt CO$_2$/yr.

**CCS**

Assessment of CCS in the pulp and paper industry has been made by using case studies at plant level and detailed analysis of integration possibilities to use excess heat for the CCS process. The result is used for calculating the potential in EU27 by including data on the specific conditions for production sites.

CCS in the pulp and paper industry has been evaluated by linking other studies of CCS at pulp mills to analysis of the geographical positions of chemical pulp and paper mills [Jönsson et al, 2010c]. Several studies of CCS at pulp mills have been made, aiming at integrating the process and use waste heat for capturing CO$_2$. As a result the need for primary energy can be reduced by about 30%, compared to a non-integrated solution.

The analysis of geographical positions uses the closeness to other point-emission sources and to CO$_2$-deposition places as criteria for positions suitable for CCS. Adding all pulp mills emitting more than 0.5 Mton CO$_2$/yr, 55 Mton CO$_2$/yr could be captured. Narrowing the potential to mills that also are situated close to large emission sources of fossil CO$_2$, reduces the potential radically (7 Mton). Including also smaller sources (> 0.1 Mt CO$_2$/yr) increases the total potential to, in total, 65 Mt CO$_2$/yr. Total CO$_2$ emissions (bio and fossil) from the pulp mills in the study are 82 Mt CO$_2$/yr.
### Table 5a. Reduction in energy use and CO₂ emissions from top-down model - Paper industry

<table>
<thead>
<tr>
<th>Energy [TWh] Policy/Market</th>
<th>Direct CO₂ emissions [Mton/yr] Policy/Market</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduction compared to Baseline</td>
<td>-107/-122</td>
</tr>
</tbody>
</table>

### Table 5b. Reduction in energy use and CO₂ emissions from and bottom-up estimates of the potential of specific measures - Paper industry

<table>
<thead>
<tr>
<th>STRUCTURAL CHANGES</th>
<th>Energy [TWh]</th>
<th>Direct CO₂ emissions [Mtonne/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total energy</td>
<td>Electricity</td>
<td>Biomass</td>
</tr>
<tr>
<td>Increased recovery of paper</td>
<td>▼</td>
<td>▼</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ENERGY EFFICIENCY IMPROVEMENTS</th>
<th>Energy [TWh]</th>
<th>Direct CO₂ emissions [Mtonne/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>New technology and process integration (generating alternative energy products)</td>
<td>-50</td>
<td></td>
</tr>
<tr>
<td>Black liquor gasification</td>
<td>-50 to -110</td>
<td>▼</td>
</tr>
<tr>
<td>Advanced drying technologies - (5-10) %</td>
<td>-25 to -50</td>
<td></td>
</tr>
<tr>
<td>Energy efficient motor systems</td>
<td>-50</td>
<td>-50</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FUEL SUBSTITUTION</th>
<th>Energy [TWh]</th>
<th>Direct CO₂ emissions [Mtonne/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>83 % of heat is below 400 °C, replace with biofuel</td>
<td>0</td>
<td>-12</td>
</tr>
<tr>
<td>Assessment of CCS in pulp and paper industry</td>
<td>+50</td>
<td></td>
</tr>
</tbody>
</table>

1. Estimated for the year 2050, based on pathway development 2. Based on current production. (▼ = decrease, quantity unknown, ▲ = increase, quantity unknown).

### 5.5.3 Paper, printing - Realisation of potentials in the pathways

According to the top-down modelling results, lacking process related constraints, the share of biofuel (included in “other”) decreases substantially over time. Even though recycling levels are expected to increase somewhat, the sector will still be primarily based on biomass as raw material. Since energy use and processes are closely linked in this sector, significant fuel substitution away from biofuel is not likely. Therefore, the development of both Baseline and pathways needs to be adjusted for the decreasing shares of biomass use. Consequently, the paper and printing sector can serve as a useful illustration of the need for basing analysis also on process and technology related data. In total, the adjustments lead to total direct CO₂ emissions from this sector close to zero. In the Market pathway, they are even negative, as a result of CCS from biomass (see Figure 9).
Energy efficiency improvements in the paper and printing industry can, as in several other energy-intensive industries, be divided into two different types. Firstly, efficiency improvements that reduce the use of fossil fuels and/or electricity and, secondly, efficiency improvements leading to an energy surplus. In the pulp industry the second type of efficiency improvement are especially interesting, since the energy surplus will be based on biomass and can thus be used for providing a range of CO₂ free energy services – CCS, electricity production, district heating - depending on the pathway.

The potential for the first type of energy efficiency improvements seems, according to the overview above, to be somewhat larger than the reduction in top-down results. Thus, in the Policy Pathway some additional energy efficiency improvements are assumed. The second type of energy efficiency improvements is assumed to be primarily used for fuel and electricity deliveries in the Policy pathway, while it would be, to a larger extent, used for CCS and district heating in the Market pathway.

The potential for additional use of biomass for fuel, mostly in non-integrated paper mills, is assumed to be utilized primarily within the Policy pathways. CCS is assumed to be primarily implemented at large mills. However, we assume that CO₂ based on both biofuel and fossil fuels are included in the development of the CCS infrastructure.

5.6 Food
The food industry uses 8% of the energy used by industry (including refineries), the major part of which consists of fossil fuel (for heat production) and electricity. There are few sector-specific estimates of reduction strategies and potentials in the food industry.

5.6.1 Food - Results from top-down model
Compared to Baseline, model results show that energy demand in the food industry will be 20-25% lower in 2050 in the Policy and Market pathways, respectively. However, contrary to the more energy-intensive sectors above, both energy use and direct CO₂ emissions increase relative to the year 2000 in all scenarios.

Figure 10. Result from the TD-model - energy supply for the Food industry sector in 2000 and in 2050 for the baseline and the two pathways, Policy and Market
5.6.2 Food - Bottom-up analyses
The food sector has not been in focus of any specific pathway study, except for the general analysis of potential use of biomass in industry [Göckeler, 2007]. Therefore, mostly general CO₂ reduction measures, as opposed to process or sector specific, are included below.

Energy efficiency measures
According to SAVE, about 90% of electricity use in the food industry is used by motor driven systems [EU SAVE 2000]. Potential savings in electricity through more efficient motor systems are estimated at 50 TWh. Other electricity use can be assumed to mainly consist of electricity for lighting, with an even higher relative potential for efficiency improvements. The food industry is also a process industry with large heat demands and, thus, with a potential for efficiency improvements through process integration. Based on the potential for cost efficient process integration in general, the potential for efficiency improvements is estimated to about 25% [Worrell et al, 2009]. Food industries operate in general at temperatures close to 100°C. This means that it would be possible for the industry to increase the use of district heating. In addition, the industry could have a potential for delivering heat to district heating systems. The amount of surplus heat that could be utilized would, however, be larger if the temperature level is increased by heat pumps.

The food industry could also deliver efficiently produced electricity by increasing co-generation of electricity and heat.

Fuel substitution
As mentioned above, the food industry is a large user of heat, more or less all of which is used below a temperature level of 400°C [Göckeler, 2007]. This means that it would, in principle, be possible to replace all fossil fuels used for heating purposes with bioenergy. Furthermore, 73% of total energy is used for heating. Consequently, the potential to increase biomass use in the European food industry is large. Heat demand below 100°C could, as an alternative, be replaced by district heating.

CCS
Industrial food industry sites represent in general too small point sources for CO₂ emissions to be applicable for CCS.

5.6.3 Food - Realisation of potentials in the pathways
For the food industry, no detailed bottom-up studies have been included in the Pathways project. Nevertheless, the literature review calls for some adjustments.

In the Policy pathway, policies are assumed to be put in place that lead to some additional energy efficiency improvements compared to the top-down results (based on the estimate in Table 6). Furthermore, in the Policy pathway, a strong fuel shift towards biomass is expected. The top-down model results include very little fuel substitution and since the prospects for biofuel use within this industry is especially good, part of this potential is assumed to be implemented also in the Market Pathway.
### Table 6a. Reduction in energy use and CO₂ emissions from top-down model - Food industry

<table>
<thead>
<tr>
<th>Policy/Market</th>
<th>Energy [TWh]</th>
<th>Direct CO₂ emissions [Mton/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduction compared to Baseline</td>
<td>-111/-132</td>
<td>-18/-22</td>
</tr>
</tbody>
</table>

### Table 6b. Reduction in energy use and CO₂ emissions from bottom-up estimates of the potential of specific measures - Food industry

<table>
<thead>
<tr>
<th>Energy [TWh]</th>
<th>Direct CO₂ emissions [Mtonne/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ENERGY EFFICIENCY IMPROVEMENTS</strong></td>
<td></td>
</tr>
<tr>
<td>Total energy</td>
<td>Electricity</td>
</tr>
<tr>
<td>Energy efficient motor systems&lt;sup&gt;1&lt;/sup&gt;</td>
<td>-50</td>
</tr>
<tr>
<td>Process integration and heat recovery&lt;sup&gt;1&lt;/sup&gt; 25%</td>
<td>-136</td>
</tr>
<tr>
<td>General electricity savings, lighting etc&lt;sup&gt;1&lt;/sup&gt;</td>
<td>-10</td>
</tr>
<tr>
<td>More efficient steam generation</td>
<td>↓</td>
</tr>
<tr>
<td>Co-generation of heat and power</td>
<td>↑</td>
</tr>
<tr>
<td>DH use below 100 oC&lt;sup&gt;1&lt;/sup&gt; (potential 174 TWh)</td>
<td></td>
</tr>
<tr>
<td><strong>FUEL SUBSTITUTION</strong></td>
<td></td>
</tr>
<tr>
<td>83 % of heat is below 400 oC, replace with biofuel&lt;sup&gt;1&lt;/sup&gt;</td>
<td>0</td>
</tr>
</tbody>
</table>

<sup>1</sup> Estimated for the year 2050, based on pathway development (↓ = decrease, quantity unknown, ↑= increase, quantity unknown).

### 5.7 Equipment goods and other industry

Energy use does not represent a large share of total costs in the equipment industry or “other” industry (including manufacturing of furniture, sport goods, toys etc, mining and textile industry). However, since they represent important industries in economic terms, the sectors still use about 8% and 12%, respectively, of the total amount of energy used in European industry (including refineries). As a consequence, the potential and realization of energy efficiency improvements in these sub-sectors are important to the development of industrial energy use at large.

These industries have many similarities and have been treated in the same way in the synthesis work. Below, the example of the equipment goods sector is described.

#### 5.7.1 Equipment goods - Results from TD-model

The model results show that energy demand in the equipment goods sector will be about 100 TWh or 20 % lower in 2050, compared to Baseline. Also here there is a clear increase in energy use compared to the year 2000. This can be explained partly by the large production increase assumed (119%) and partly by lower sensitivity to changing energy prices. Also
total CO₂ emissions will increase slightly, compared to the current level.

5.7.2 Equipment goods - Bottom-up analysis
The equipment goods industry was not included in any study in the pathway project except for the biomass to heat study. As in the food industry above, focus is therefore put on general measures.

Energy efficiency measures
Electricity use in the Equipment goods industry is to a large extent used for motor driven systems, but also for heating, lighting etc. Of total electricity use of 150 TWh in year 2000, about 50% is used in motor systems [EU-SAVE, 2000], which translates to a potential for efficiency improvements at about 40 TWh in 2050. The potential for efficiency improvements in other electricity use is difficult to estimate. However, with a large share of electricity use for lighting, an average of about 40% (with a higher potential for lighting and lower for other electricity use) should be realistic.

Fuel substitution
According to the study of possibilities to replace fossil fuels with bioenergy, based on German industry, 90% of the energy used for heat in the equipment goods industry could be replaced by bioenergy. This means that the industry would use additionally 240 TWh of biomass and that CO₂ emissions would be reduced with 40 Mton. 64% or 190 TWh of the heat is used below 100°C and could also be generated with district heating.

Figure 11. Result from the TD-model - energy supply for the Equipment goods industry sector in 2000 and in 2050 for the baseline and the two pathways, Policy and Market
Table 7a. Reduction in energy use and CO₂ emissions from top-down model - Equipment goods industry

<table>
<thead>
<tr>
<th>Reduction compared to Baseline</th>
<th>Energy [TWh] Policy/Market</th>
<th>CO₂ emissions [Mtonne/yr] Policy/Market</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-98/-113</td>
<td>-11/-14</td>
</tr>
</tbody>
</table>

Table 7b. Reduction in energy use and CO₂ emissions from bottom-up estimates of the potential of specific measures - Equipment goods industry

<table>
<thead>
<tr>
<th>ENERGY EFFICIENCY IMPROVEMENTS</th>
<th>Energy [TWh]</th>
<th>Direct CO₂ emissions [Mtonne/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total energy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biomass</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂ change</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ENERGY EFFICIENCY IMPROVEMENTS</th>
<th>Total energy</th>
<th>Electricity</th>
<th>Biomass</th>
<th>CO₂ change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy efficient motor systems¹</td>
<td>-40</td>
<td>-40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>General energy efficiency lighting etc¹</td>
<td>-55</td>
<td>-55</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy recovery - reduction of use of fuel for heat¹</td>
<td>-30</td>
<td>-30</td>
<td>-10</td>
<td></td>
</tr>
<tr>
<td>More efficient steam generation and CHP</td>
<td>↓</td>
<td>↓</td>
<td></td>
<td>↓</td>
</tr>
<tr>
<td>DH use at temperatures below 100 °C¹ (potential 190 TWh)</td>
<td>↓</td>
<td></td>
<td></td>
<td>↓</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FUEL SUBSTITUTION</th>
<th>Total energy</th>
<th>Electricity</th>
<th>Biomass</th>
<th>CO₂ change</th>
</tr>
</thead>
<tbody>
<tr>
<td>83 % of heat is below 400 °C, replace with biofuel¹</td>
<td>0</td>
<td>-70</td>
<td>+240</td>
<td>-40</td>
</tr>
</tbody>
</table>

¹ Estimated for the year 2050, based on pathway development. (↓ = decrease, quantity unknown).

5.7.3 Equipment goods - Realisation of potentials in the pathways

In the equipment goods and other industry sectors, the top-down modelling results are adjusted for two factors. Firstly, some additional energy efficiency measures are assumed in the Policy pathway. Secondly, fossil fuel use is assumed to be partly substituted for bioenergy in the Policy pathway and for district heating in the Market pathway.

5.8 Mineral oil refineries

For the Pathway scenarios, the production volume in the refinery sector is not based on projections in literature, but on total demand for oil from other sectors of the European energy system, the major part of which is linked to the transportation sector. The transportation sector is assumed to be transformed and rely increasingly on use of electricity and second generation biofuel. As a result, total production in mineral oil refineries is assumed to decrease drastically, contrary to all other industry sectors. The remaining production capacity of the refineries in 2050 is thus estimated at only 45% and 44% of today’s capacity in the Policy and Market scenario, respectively. In the Baseline scenario oil use is 22% higher in 2050 than today’s use.
The analysis of the refinery industry, below, is thus made based on the following important assumptions:

- The production volume is expressed in physical terms, and not in value added. Since the product mix changes towards more sophisticated products with higher values, the decrease in value added should be less than in product volume.

- The analysis of the refinery sector includes here conventional production based on mineral oil only. With time, the refinery sector may increasingly include production of transportation from biomass fuel. In the pathway project, however, detailed effects of such a transformation have not been studied.

- Total biomass demand for biofuel production is, however, included in the overall pathways synthesis. In total, the Pathway project points at a use of biomass for production of transportation fuel at between 558 TWh and 844 TWh in 2050 [European Energy Pathways, 2010].

In a study made by CONCAWE, an association of the European oil industry, options on how to meet the EU requirement for CO₂ reduction is investigated. Measures for CO₂ reduction in the refinery sector included in this study are:

- energy efficiency improvements,
- refinery fuel switching,
- changes in type of crude oil used, and
- Carbon Capture and Storage (CCS) in refineries.

CONCAWE also points out that due to changes in product mix, specific energy demand, without the implementation of energy efficiency measures, is expected to increase.

5.8.1 Refinery – Potential for CO₂ emission reduction

The following studies of the refinery industry are included in Pathways:

- Mapping of the refineries in EU [Johansson, 2010a].
- The Pathway study of CCS in heavy industry includes CCS in refineries [Rootzén et al, 2009].
- Analysis of the CO₂ reduction potential when hydrogen used at the refinery is produced from gasified biomass and integrated with the refinery [Johansson et al, 2010b].
- A study of the possibilities to reduce energy demand by more efficient use of hydrogen has been made as a case study of two refineries [Andersson and Vadenbo, 2010].

Overall sector analysis

A mapping of the 33 most complex refineries in Europe has been made to find out the surrounding conditions of refineries to evaluate the potential for contributing to a sustainable development [Johansson, 2010a]. Surrounding conditions examined are

- Possibilities to deliver excess heat to a district heating system
- Power generation on site
- Natural gas grid
- Integration with petrochemical clusters
- Kraft pulp and paper plants
- Harbour
- CCS storage possibilities

The results from this study are integrated under each section below.
**Structural changes**

Increased demand of high-grade refinery products will result in a higher specific energy demand due to an increased demand for hydrogen. Hydrogen production from natural gas will increase both energy demand and process CO₂ emissions.

Structural change through integration of biofuel production in the refinery sector, is, as noted above, not included here.

**Energy efficiency measures**

According to the sector mapping, 22 of the 33 refineries are situated close to a district heating system Johansson, 2010a]. This means that the opportunities for using excess heat for other purposes and thus decrease energy demand in other sectors should be good. Based on district heat availability from some refineries and the number of refineries close to district heating networks, the potential in Europe can be estimated to 25-30 TWh in 2007.

The majority of the refineries in the study generate power on-site and can export excess electricity. Energy efficiency measures could reduce the potential for electricity generation. The potential for efficiency improvements through process integration, leading to reduced demand for primary heat, is estimated to about 10% [Worrell et al, 2009].

Many of the refineries in the survey are situated close to a petrochemical cluster. This could imply potential benefits of co-siting, such as increased use of recovered heat and increased power generation due to improved design of utility networks. Worrell et al estimates a general energy reduction potential of 5% for process integration between different activities at one site [Worrell et al, 2009].

Product development, driven by regulation to find products that have less negative effects on health and environment, leads to an increased hydrogen demand at the refineries. Hydrogen production is an energy demanding process and more efficient use of hydrogen would lead to energy savings. Based on case studies at two refineries in Sweden, there are possibilities to reduce hydrogen production by improving the recovery of hydrogen rich off-gases [Andersson and Vadenbo, 2010].

**Fuel substitution**

Producing hydrogen used at the refinery from gasified biomass and integrate the production with the refinery would reduce direct CO₂ emissions at the refinery, due to reduced use of natural gas [Johansson, 2010b]. However, the impact on global CO₂ emissions depend on the alternative use of biomass.

Butane is one product fraction that today is used as fuel in the refinery. There is a possibility to use butane as raw material in chemical industry and instead use natural gas for energy. This would decrease the CO₂ emissions at the refinery.

**CCS**

The potential for CCS has been calculated for two process options in the refinery industry [Rootzén et al, 2009]. If carbon is captured by oxyfuel combustion, 94 Mt of CO₂ /yr could be captured. For post combustion capture the potential is 116 Mt of CO₂/yr. Additional energy use is assumed to be small, since the process is expected to, at least partly, utilize excess heat at the refinery. The survey of the 33 complex refineries show that 2/3 have a storage site within 100 km [Johansson, 2010a].
**Table 8a. Reduction in energy use and CO₂ emissions based on expected refinery activity (structural change) in the Pathways - Refinery industry**

<table>
<thead>
<tr>
<th></th>
<th>Energy [TWh]</th>
<th>Direct CO₂ emissions [Mtonne/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Policy/Market</td>
<td>Policy/Market</td>
</tr>
<tr>
<td>Reduction compared to Baseline</td>
<td>-546/-553</td>
<td>-130/-132</td>
</tr>
</tbody>
</table>

**Table 8b. Reduction in energy use and CO₂ emissions based on quantified measures identified - Refinery industry**

<table>
<thead>
<tr>
<th></th>
<th>Energy [TWh]</th>
<th>Direct CO₂ emissions [Mtonne/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ENERGY EFFICIENCY IMPROVEMENTS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total energy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biomass</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂ change</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrogen recovery²</td>
<td>↓</td>
<td>↓</td>
</tr>
<tr>
<td>General process integration</td>
<td>-31</td>
<td></td>
</tr>
<tr>
<td>Co-generation of heat and power</td>
<td>↓</td>
<td>↑</td>
</tr>
<tr>
<td>Energy recovery – district heat delivery</td>
<td>+25 to -30</td>
<td>↓</td>
</tr>
<tr>
<td>Co-siting¹</td>
<td>-15</td>
<td></td>
</tr>
<tr>
<td>Energy efficient motor systems¹</td>
<td>-10 -10</td>
<td></td>
</tr>
</tbody>
</table>

**FUEL SUBSTITUTION**

| Increased hydrogen production from biomass instead of NG² | +9 | +4 | +54 | -10 |
| Use NG instead of butane²                                 |    |    |     | -7  |

<table>
<thead>
<tr>
<th>CCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assessment of CCS in refineries²</td>
</tr>
</tbody>
</table>

¹ Estimated for the year 2050, based on pathway development
² Based on current production. (↓ = decrease, quantity unknown, ↑ = increase, quantity unknown).
5.8.2 Refinery - Realisation of potentials in the pathways

For the refinery sector, total development is based on the development of total physical demand for its products from the energy system in each pathway. As a consequence, the development differs largely to that in other sectors, in that a declining (physical) production is expected.

The major effect on total emissions and energy use is thus a direct result of the reduced production capacity. The least energy efficient sites are expected to be taken out of production, resulting in a reduction in average specific energy use, which can be expected to cancel out the trend of increasing specific energy use. In addition from these, structural, effects, additional energy efficiency improvements are included, based on the overview above (see Table 8).

The potential for CCS and for delivery of district heating is assumed to be reduced in relation to the reduction in total production capacity, which would translate to a CCS potential of 45 Mton/yr The implementation is assumed to be 50% and 75%, respectively, in the Policy and Market pathways.

![Figure 12](image-url)  
**Figure 12.** Development of energy use and CO₂ emissions in the Refinery sector based on projected use of oil in the pathway analysis and including the suggested measures in the table above.
Based on the sub-sector syntheses above, some conclusions can be drawn for the aggregate European industry sector. On such an aggregate level, and in the long-term perspective used here, there are significant uncertainties associated with the results. Nevertheless, the overall results are useful for increasing understanding of the roles of industry in a climate policy context.

The development of energy use and CO₂ emissions in European industry is estimated for the Policy and Market pathways. The estimate is based on projections of strongly increasing production volumes (in terms of value added). The approach taken has been to estimate techno-economic emission reduction potentials that take constraints, based on for instance process-related practical conditions and available infrastructure, into account. Finally, implementation rates for these potentials have been used that are estimated to be realistic (albeit relatively high), given strong climate policy measures.

Decreasing CO₂ emissions despite strongly increasing production volumes
The results show decreasing development of total energy use and strongly decreasing CO₂ emissions. According to this synthesis, the total emission levels in 2050 could be up to 50% and 60% lower in the Policy and Market pathways, respectively, as compared to the corresponding levels in year 2000 (Figure 13). Since the assumed total production would more than double during the same period, the CO₂ emissions per value added would decrease by about 80%.

A large share of these major reductions would be realized should past development trends, in terms of decreasing specific energy use and reactions to energy price changes, continue into the future. This synthesis shows that in most industrial sectors there are technological potentials for improvements, which would make such a development possible. However, realization would require considerable structural changes in terms of product and process development and investments in energy efficiency improvement measures. Advances in process technology and the realization of CCS would increase the reductions in specific emissions beyond the historical levels.

All types of measures necessary to achieve large reductions
When aggregated for the entire European industry (Figure 13), the synthesis results clearly show that in order to achieve reduced emission levels from industry, in the face of continuing increases in production volumes, all types of measures are needed and contribute significantly to the development. The differences between the two pathways primarily reflect the primary assumptions behind each pathway. In the Policy pathway, these include a stronger focus on demand-side energy efficiency improvements and fuel substitution for biomass. In the Market
pathway, greater implementation of CCS and conversion to electricity and district heating lead to lower levels of direct emissions.

Structural change and energy efficiency improvements are important measures throughout the industry and account for, in total, more than half of total emission reductions. However, the distinction between these types of measures is inherently uncertain and primarily indicative. Structural change, as shown in the above figures, is based primarily on the results from the top-down model and may include a combination of measures.

Fuel substitution for biomass is primarily an important option in the pulp and paper and food industries, although it may also play a significant role in primary metals industries if new processes are introduced to produce charcoal, as well as in the chemical industry if biomass becomes more widely used as a raw material. The potential for CCS in industry is primarily linked to large, energy-intensive plants with relatively concentrated CO₂ streams, which are found primarily within the steel, cement, refinery, and pulp and paper industries. Moreover, in these industries, available surplus heat often makes the conditions for CCS even more favourable.

Energy-intensive industry important for success
Energy-intensive industry, which here encompasses the sub-sectors of primary metals, chemicals, pulp and paper, non-metallic minerals, and refineries, accounts for, in total, about 80% of the total emissions from industry and 83% of the estimated reductions in emissions. Emission reductions in the energy-intensive industry are more dependent upon capital-intensive technology investments and infrastructural conditions than in, for instance, the equipment goods sub-sector. This implies a substantial potential for large, step-wise reduction measures, while it also indicates a higher level of dependency on energy market conditions, economic development, and infrastructure. Therefore, the inclusion of geographical information and infrastructural parameters in the Pathways analyses is crucial. Furthermore, this means that the directions for development in these sectors are particularly uncertain.
The large share of reductions ascribed to the refinery sector (Figure 14) reflects primarily the assumptions made regarding the growth of this sector. In the refinery sector, production volume is expressed in terms of physical demand for oil products in the pathways and, in contrast to all other sectors, is assumed to be strongly decreasing. In comparison, the reductions in the pulp and paper sector, included in Figure 14, appear small. This is partly a result of the sector being largely dependent upon biomass for energy and that energy efficiency measures consequently have less of an impact on direct fossil-based CO₂ emissions.

Industry also plays a significant role in reducing indirect emissions

All the figures above describe the development of direct fossil CO₂ emissions from industry. Industrial energy use, and the industrial energy system in total, impact also indirectly on total CO₂ emissions. These indirect effects include the use of district heating and electricity, but also industry-based co-generation, district heating deliveries and, since biomass is a limited resource, changes in the use of biomass for fuel. The total changes in energy flows into and out of the “industrial energy system” may be substantial, depending on the direction of development (Figure 15). The potential for increased use of biomass for energy in industry is, for example, highly dependent upon the total demands for biomass in a future society, which can be expected to increase dramatically. The potential for increasing use and the delivery of district heating in industry as a result of intra-industry integration within industrial clusters may be substantially larger. Such analyses, including geographical information, have been initiated within the Pathways project but the full potential is as yet uncertain.

The total impact on global CO₂ emissions depends on the parallel development of the energy system as a whole. The “global” emission change associated with biomass use depends therefore on the alternative use (if any) of biomass resources. Likewise, reduced electricity use in Policy pathway year 2050 compared to the baseline in 2050 will result in a reduction of about 600 Mtonne of indirect CO₂ emissions per year if electricity is produced in conventional coal plants, but there will be no change at all in emissions if electricity production is CO₂-free. In the Policy and Market pathways, an almost CO₂-free electricity production system is foreseen by 2050.

![Figure 14. Development of CO₂ emissions in the Policy and Market pathways, divided according to industrial sub-sector. The estimate for refineries are based on the future demand for oil products in the pathways, and the values do not include production of transportation fuels from biomass.](image-url)
Figure 15. Industrial energy use and deliveries in the year 2050 for the Market and Policy pathways, that could imply indirect effects on total CO₂ emissions.

However, CO₂-free power production does not necessarily make electricity efficiency improvements less valuable, since the prospects for realizing such a development of the power system improve substantially with decreasing or stabilizing levels of electricity demand.

**A coherent and extensive analysis of industrial energy use is needed**

Industrial development is important for a successful climate policy through its impact on both direct and indirect CO₂ emissions. To understand fully the complexities of industry, especially energy-intensive industry, and the potential policy impacts, a coherent and extensive analysis of industrial energy use is needed. This type of analysis includes both detailed studies of potential measures and technologies, the development of aggregate techno-economic potentials, energy policy design, and overall syntheses of the results. Furthermore, the interconnections between energy use and the development of production volumes, production structures, and products need to be better understood and included in an integrated analyses framework.

This synthesis is performed as an ex-post exercise, based on analyses presented in other research studies. There are significant uncertainties associated with the presented results. Nevertheless, the overall results are useful for increasing understanding of the roles of industry in a climate policy context. For the future, it would be valuable to use the experiences gained here to design the synthesis work in parallel to the analytical work and construct it on a more rigid methodological framework.


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Pathways to sustainable European energy systems

The European pathways project is a five year project with the overall aim to evaluate and propose robust pathways towards a sustainable energy system with respect to environmental, technical, economic and social issues. The focus is on the stationary energy system (power and heat) in the European setting. Evaluations will be based on a detailed description of the present energy system and follow how this can be developed into the future under a range of environmental, economic and infrastructure constraints. The proposed project is a response to the need for a large and long-term research project on European energy pathways, which can produce independent results to support decision makers in industry and in governmental organizations. Stakeholders for this project are: the European utility industry and other energy related industries, the European Commission, EU-Member State governments and their energy related boards and oil and gas companies. The overall question to be answered by the project is:

How can pathways to a sustainable energy system be characterized and visualized and what are the consequences of these pathways with respect to the characteristics of the energy system as such (types of technologies, technical and economic barriers) and for society in general (security of supply, competitiveness and required policies)?

This question is addressed on three levels; by means of energy systems analysis (technology assessment and technical-economic analysis), a multi-disciplinary analysis and an extended multi-disciplinary policy analysis. From a dialogue with stakeholders, the above question has been divided into sub-questions such as:

- What is the critical timing for decisions to ensure that a pathway to a sustainable energy system can be followed?
- What are "key" technologies and systems for the identified "pathways" - including identification of uncertainties and risks for technology lock-in effects?
- What requirements and consequences are imposed on the energy system in case of a high penetration of renewables?
- What are the consequences of a strong increase in the use of natural gas?
- What if efforts to develop CO₂ capture and storage fail?
- Where should the biomass be used – in the transportation sector or in the stationary energy system?
- Are the deregulated energy markets suitable to facilitate a development towards a sustainable energy system?
- Will energy efficiency be achieved through free market forces or regulatory action?
- What are the requirements of financing the energy infrastructure for the different pathways identified?

In order to address the sub-questions in an efficient and focussed way the project is structured into 10 work packages addressing topics such as description of the energy infrastructure, energy systems modelling, technology assessment of best available and future technologies and international fuel markets. In planning of the project significant efforts have been put into ensuring that the project should not only be strong in research but also in management, communication and fundraising.

The global dimension will be ensured through integration with the other three regional AGS pathway projects in the Americas, East Asia, and India and Africa.

More information at Pathways website: www.energy-pathways.org
The Alliance for Global Sustainability

The Alliance for Global Sustainability (AGS) brings together four of the world’s leading technical universities – the Massachusetts Institute of Technology, The University of Tokyo, Chalmers University of Technology and the Swiss Federal Institute of Technology – to conduct research in collaboration with government and industry on some of society’s greatest challenges.

The AGS represent a new synthesis of multidisciplinary and multi-geographical research that draws on the diverse and complementary skills of the AGS partners. In addition to academic collaborations each of the universities has extensive experience in working with stakeholders, particularly a growing number of visionary leaders from industry who recognise their fundamental role in achieving sustainable development.

More information at AGS website: globalsustainability.org
Opportunities for reducing CO$_2$ in European industry until 2050
- a synthesis of industry analyses within the Pathway project

European industry has the potential to contribute substantially to both reduced CO$_2$ emissions and development towards sustainability. However, to reach low emission levels, all types of measures, including structural change, energy efficiency improvements, fuel substitution and carbon capture and storage are needed. Energy-intensive industries play a key role in this process, and have substantial potential for large step-wise reduction measures. However, implementation of these measures is crucially dependent upon energy market conditions and infrastructure, and therefore on interactions with other parts of the energy system.

Within the Pathway project a number of sub-projects directed towards the industrial sector have been included, in which the development of specific industrial sub-sectors and/or types of measures for reducing CO$_2$ emissions are studied. These results provide a basis for estimating the potential contributions of technological and structural changes within industry to the development of overall energy systems pathways. In this report, a synthesis for the entire European industry sector is presented that strive to utilize fully the knowledge gained in all these studies, supplemented with data in the literature.