European chemistry for growth

Unlocking a competitive, low carbon and energy efficient future





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Foreword

Cefic initiated a roadmap to explore the impact, opportunities and risks of various energy and technology development scenarios for the European chemical industry in the timeframe from 2020 to 2050. Cefic commissioned Ecofys to perform analyses and bring forward key conclusions and recommendations from their independent viewpoint, in close collaboration with the sector.

This Roadmap shows that products of the chemical industry are used in all sectors of the economy. This makes the industry a powerful engine for innovation and sustainable development. Realising our potential, we will continue to work with our value chain partners and other stakeholders to develop the chemistry to enable innovative energy efficient and low carbon solutions.

For this to happen, a complete chemical industry value chain from basic chemicals to consumer products is needed in Europe. Today this is seriously at risk. In a persisting situation of continued fragmentation, a policy shift towards reducing rather than further increasing EU energy and policy costs is urgently needed to ensure the competitiveness of the European chemical industry.

The chemical industry has a long track record of improving its energy and resource efficiency, thereby lowering its greenhouse gas emissions intensity. It is recognised that innovation is crucial to ensure further improvements and develop breakthrough technologies that enable a low carbon and energy efficient European chemical industry.

European and national policy makers have a key role to play towards an innovation-friendly environment in which European industry can thrive, ideally in a global level playing field. It is essential that the energy and climate policy framework in the EU stimulates sustainable and efficient growth. Under these conditions, innovations and investments that can mitigate global emissions will deliver their full potential.

We believe in the future of the chemical industry in Europe and its capacity to create wealth and provide healthy living and high-quality jobs. A thriving chemical industry is an essential part of the solution for the challenge of climate change. We invite you to explore Europe's energy and climate future with us.

Kurt Bock - President of Cefic and CEO of BASF

Tom Crotty - Chairman of Cefic Energy programme council and Group Director - INEOS

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Executive summary

The chemical industry has a crucial role in Europe's transformation to a more energy efficient and low carbon future. The opportunities the sector offers and the challenges it faces are explored under four scenarios investigated in this Roadmap. Key findings are:

- 1. Products of the chemical industry enable significant energy efficiency improvements and greenhouse gas emissions reduction in all sectors and are needed for Europe's transformation to a low carbon economy. This enabling effect is likely to grow in the future. The 2010 production of the European chemical industry is estimated to contribute to over 1.5 billion tonnes of avoided greenhouse gas emissions during product use, equivalent to roughly 30% of the total European greenhouse gas emissions in 2010.
- 2. The competitiveness and growth of the European chemical industry value chain and its ability to attract investments will be damaged by isolated actions in terms of climate and energy policies, leading to rising costs for European operations:
 - **Current energy and feedstock price differences** with key competing regions outside Europe jeopardise the global competitiveness of Europe's chemical industry and the value chain it supports. These differences are due to energy prices and policy costs. Limiting fuel mix choices, including restrictions on exploiting unconventional gas in a sustainable way, would worsen Europe's disadvantage, hamper investments and could limit the development of some crucial greenhouse gas emission abatement options.
 - Increasing differences in policy costs in a continued, fragmented policy framework are estimated in direct CO₂ costs alone at € 1.7 billion per year in 2030 and € 3.1 billion in 2050 for the European chemical industry. This poses a threat to the competitiveness of the European chemical industry and its ability to meet the growing demand for chemical products with production in Europe. Unilateral European climate action to reduce greenhouse gas emissions by 80–95% in 2050 compared to 1990 would have a further deteriorating effect on production in Europe and the resultant trade ratio. The level of greenhouse gas emissions reduction achieved in Europe would, in case of increasing imports, be achieved at the expense of increased emissions elsewhere. There would be no overall reduction in global greenhouse gas emissions or even a potential increase.
- 3. Fragmentation of policies and isolated EU approaches will reduce the European chemical industry's potential for energy and greenhouse gas efficiency solutions and might increase global greenhouse gas emissions. Between 1990 and 2010, the European chemical industry was able to achieve an absolute greenhouse gas emission reduction of 50% as estimated previously and attract investments. Energy efficiency improvements will continue to contribute the most to future reduction of greenhouse gas emissions. N₂O abatement and changes in the fuel mix for heat generation are other important options available to the chemical industry itself. All above options rely on further innovation and can achieve a greenhouse gas emissions reduction of 15 to 25% by 2030 compared to 2010 levels. Under a level playing field scenario, the European chemical industry could meet the growing demand for chemical products with production in Europe at a reduced greenhouse gas emissions intensity. However, it

should be noted that the emissions intensity is higher under a continued fragmented policy framework due to, among other reasons, a limited growth of the industry from relocation of production to outside of Europe.

4. Deeper greenhouse gas emissions reduction is technically possible by decarbonisation of the power sector and, in addition, for the 2030–2050 timeframe, by carbon capture and storage applied to emissions from the chemical industry. These options are costly and require technological breakthroughs. They face several barriers that are largely outside the control of the chemical industry.

It is essential that the energy and climate policy framework in the EU stimulates sustainable and efficient growth. Under these conditions, innovations and breakthrough technologies that can mitigate global emissions will deliver their full potential. A stable and predictable policy framework, dynamic enough to adapt to a changing global energy and climate policy outlook, will create increased certainty for business to undertake the path to a more energy efficient and low carbon future.

Products of the chemical industry are important for all sectors of the economy to increase their energy efficiency and reduce greenhouse gas emissions. This enabling effect is likely to grow in the coming decades.

While the chemical industry is a major energy user, responsible for about a quarter of industrial final energy use in Europe, its products help to save energy and reduce greenhouse gas emissions when they are used. Chemistry enables energy saving solutions in all sectors of the economy. A few examples, amongst many, are chemical solutions for insulation and efficient lighting in the buildings sector, lightweight materials for use in the transport sector as well as materials for wind turbines and solar cells for renewable energy generation. The products manufactured by the European chemical industry in 2010 are estimated to contribute to over 1.5 billion tonnes of avoided greenhouse gas emissions during their use. That is equivalent to roughly 30% of the total European greenhouse gas emissions in 2010.

This enabling effect is likely to further increase, because there is still untapped potential to apply existing solutions and there are new low carbon technologies entering the market. Examples of products already in the commercialisation phase are vacuum insulation panels to reduce energy use, advanced solar cells for renewable power generation, and innovative packaging solutions that reduce food waste. A further shift to nitrate based fertilisers will reduce emissions from fertiliser use in the agricultural sector.

The European chemical industry will continue to seek enhanced cooperation with other stakeholders along their value chain to foster development and greater uptake of these solutions, to realise energy and greenhouse gas emissions savings. Also, the industry will continue to contribute to further developing methodologies to quantify the contributions chemicals make to energy savings and overall greenhouse gas emissions reduction along the value chain. A range of current and future technologies is available to the European chemical industry to continue its long track record in energy efficiency and emissions intensity improvements. Growth and innovation are essential to achieve deep net greenhouse gas emissions reduction in the decades to come.

The demand for products of the chemical industry will continue to grow, driven by economic growth and the innovative solutions that the chemical industry provides. A competitive **global level playing field** in terms of energy and policy costs results in a European chemical industry that can meet the growing demand for chemical products from a growing European production capacity. The energy intensity per unit of sales could decrease by about 25% in the period between 2010 and 2030 and further afterwards. This results in constant level energy use in the period up to 2030 and a slight increase towards 2050 (Figure 1a).









From Figure 1b it can be concluded that there are several routes to achieving greenhouse gas emissions reduction under a level playing field scenario:

- Ambitious energy efficiency improvements could reduce greenhouse gas emissions by about 35% in 2050 as compared to a situation without further greenhouse gas intensity developments beyond 2010 (i.e. the upper line in figure 1b). There are, however, significant differences in the energy efficiency potential between the different subsectors, regions and chemical sites depending on, for example, actions already undertaken.
- 2. Changes in the fuel mix for heat generation used to meet the heat demand for chemical processes (e.g. a further shift towards natural gas or biomass) would contribute to a further reduction of about 10% by 2050 as compared to a situation without greenhouse gas intensity improvements beyond 2010. Part of this greenhouse gas emissions reduction could be offset by greenhouse gas emissions in the cultivation of the biomass concerned.
- 3. N_2O emissions, a greenhouse gas emitted in the production of nitric acid and some other chemical products, will become close to zero. This option offers a similar potential as changes to the fuel mix for heat generation to reduce greenhouse gas emissions in the chemical industry towards 2050.

The above three options together, which remain under control of the chemical industry itself, have the potential to reduce the emissions intensity by 40% in 2030 and 55% by 2050 as compared to a situation without further improvements in the greenhouse gas intensity beyond 2010. These options would reduce greenhouse gas emissions by **15% in 2030 compared to absolute 2010 levels with stabilisation around these levels towards 2050,** building on an achieved reduction of 50% in 2010 compared to 1990 as previously estimated in other studies. The Roadmap results show that less reduction in greenhouse gas emissions intensity of the European chemical industry would be realised with a **continued**, **fragmented policy framework**. Under such policy conditions, reductions in greenhouse gas emissions intensity would be approximately 30% in 2030 and less than 50% in 2050 compared to 2010 (Figure 1c). The reduction in greenhouse gas emissions intensity is less in this scenario compared to the level playing field due to, among other reasons, a limited growth from relocation of production to outside Europe. Higher absolute greenhouse gas emissions reduction would be achieved by these options in Europe under such and other scenarios of fragmented action, up to 25% absolute greenhouse gas emission reduction to outside of production to outside compared to 2010. However, this would happen at the expense of relocation of production to outside of Europe, with no overall reduction in global greenhouse gas emissions or even a potential increase.

Figure 1c Greenhouse gas emissions and contribution of greenhouse gas emission reduction options from 2010 to 2050 under a continued fragmented policy framework. Reductions in greenhouse gas emissions intensity are less when compared to the level playing field scenario in Figure 1b



4. Deeper reductions in greenhouse gas emissions are possible by decarbonising the electricity production in Europe and by carbon capture and storage (CCS) applied to emissions from the chemical industry. These options are costly and require technological breakthroughs. They face several barriers that can, to a more limited extent, be steered by the chemical industry itself. For CCS, these barriers include the lack of public acceptance, large infrastructure requirements and questions around the feasibility and cost effectiveness of the technology for smaller, dispersed emission sources. Decarbonising the electricity sector comes with challenges related to grid and other infrastructure requirements to incorporate a large share of intermittent renewable electricity sources.

This Roadmap did not quantitatively assess the end-of life emissions outside the chemical industry related to the use of fossil feedstock. But it did assess the options to reduce the fossil feedstock

requirement. This roadmap identifies potential for bio-based feedstock and increased use of recycled products.

All the options described above rely on **innovation**, **which is crucial** to achieve deep greenhouse gas emissions reduction and continued energy efficiency improvements globally. Important research areas for the chemical industry include advanced biomass conversion processes, process improvements, and the utilisation of carbon dioxide as raw material (Carbon Capture and Utilisation, CCU). No quantitative estimates were made for the potential of CCU, it is still in very early stage of development. The chemical industry can and will deliver breakthrough technologies from a European manufacturing base, but only if Europe remains a competitive place attracting investments.

The competitiveness and growth of the European chemical industry value chain and its ability to attract investments will be damaged by isolated actions in terms of climate and energy policies, leading to rising costs for European operations

Differences in energy and feedstock prices as well as energy and climate policy costs between Europe and the rest of the world determine whether growing demand for chemical products will be met by production in or outside of Europe. Current energy and feedstock price differences with key competing regions outside Europe jeopardise the competitiveness of Europe's chemical industry and the value chain it supports. If such differences were to persist, and in addition, policy cost differences were to further increase, for example due to policy-related levies on electricity prices in the EU and unfavourable EU emissions trading system rules, this would result in a negative trend in the trade balance for basic chemicals and lead to significant carbon leakage. The direct CO_2 costs under a scenario of a continued, fragmented policy framework are estimated at \in 1.7 billion per year of direct CO_2 costs alone in 2030, rising to \in 3.1 billion in 2050. This even excludes CO_2 and other policy costs passed on via the electricity bill.

The European chemical industry would, in this case, go from a positive to a negative trade ratio between 2030 and 2050. Such a scenario would see no further growth in production for Petrochemicals in Europe. Imports would further increase in the timeframe beyond 2030, despite growing demand for chemical products. There is a strong value chain integration between the energy-intensive basic chemical industry and the less energy-intensive parts where basic chemicals are used. Weakening the competitive position of the basic chemical industry will also negatively affect the other parts of the chemical industry.

The extreme case of a strengthened, unilateral decarbonisation by Europe without global action could lead to very high energy and climate policy cost differences between Europe and the rest of the world. This would have a strong deteriorating effect on production and trade balance for the energy-intensive parts of the chemical industry in Europe (Figures 2a and 2b). Under such a scenario, the energy-intensive subsectors will have lost their trade surplus between 2020 and 2030. Between 2030 and 2050, production would start to decline, due to a lack of investment and potentially even divestments in Europe. Europe would then import the greenhouse gas emissions related to its demand for chemical products. Absolute greenhouse gas emissions reduction in Europe, required by

the unilateral targets would be achieved at the expense of lower production in Europe and increased emissions elsewhere, with no overall reduction of global greenhouse emissions or even potentially an increase.









The competitiveness of the European chemical industry is seriously threatened in the absence of a global level playing field in terms of energy and policy costs. Figure 2a shows that with an increasing demand for chemical products over time, the level of European production will be retained in Europe under a global level playing field, whereas unilateral climate action would move production elsewhere. The European chemical industry is looking for measures that ensure comparable policy costs in the key economic regions. These measures should ensure that greenhouse gas emissions reduction takes place at the lowest possible cost. With globally converging energy and policy costs, the European chemical industry will continue to attract investment and keep a positive overall trade balance over time. This would result in employment and value creation.

The energy and climate policy framework in the EU should stimulate sustainable and efficient growth of the chemical industry in Europe to attract investment and enhance future innovations.

The current policy framework in Europe poses threats to the competitiveness of the European chemical industry. It thereby undermines its ability to attract investment and to provide further innovative solutions to increase energy efficiency and reduce greenhouse gas emissions. The EU emissions trading system, with an ex-ante allocation, limits the efficient growth of the manufacturing industry in Europe. Non-harmonised and restricted compensation for increased electricity costs creates differences in competitiveness between EU Member States. Sometimes, non-coordinated or excessive support for renewable energy may result in significant cost burdens to industry.

Energy security, competitive energy prices and climate protection are all important pillars of European policy. However, the current EU energy and climate framework drives up energy related costs and generates uncertainty for needed investments. Limiting fuel mix choices, including restrictions on exploiting unconventional gas in a sustainable way, would worsen Europe's disadvantage and hamper investments and could limit some crucial greenhouse gas emission abatement options.

The chemical industry in Europe calls on policy makers to provide a policy framework that supports sustainable and efficient growth of the European industry:

Europe should continue its efforts towards global rather than unilateral action against climate change. In the absence of a global climate change agreement, the design of the carbon market and further climate policy post-2020 should be further improved to promote efficient production and production growth in Europe. Measures to support the competitive position of the European chemical industry should be stable, predictable and coordinated across Europe. They should also avoid unnecessary cost burdens to European industry. Furthermore, the framework should be designed to incentivise the innovations required for deep greenhouse gas emissions reduction.

A truly European energy policy should be developed, including fully integrated and well-functioning electricity and natural gas markets. This should guarantee a diverse and more competitive energy supply in Europe and allow for sustainable exploration of new forms of energy, such as

unconventional gas. Renewable energy support schemes should be simplified and more coordinated across Europe. Policy makers should direct the energy portfolio towards cost-effective renewable and alternative energy options that can serve our energy needs without excessive additional back-up capacity and infrastructure costs.

The policy framework should take into account the role of the chemical industry in enabling energy efficiency and economy-wide greenhouse gas emissions reduction. Sustainable consumption should be further incentivised, focusing on the full life cycle performance of products and applications, taking on board the latest developments in methodologies.

Research and development support for innovation should facilitate new breakthrough technologies in pre-competitive phases and should focus on innovative solutions across the borders of individual sectors. Cross sector cooperation is vital in the field of further energy efficiency improvements and in the area of new innovative product solutions.

The policy package should enable market-oriented, cost-efficient technologies. It should help to overcome barriers such as public acceptance to and regulatory uncertainties surrounding new innovative technologies. A suitable support framework for the development of bio-based chemistry should be developed via standardisation of sustainability criteria for biomass, stimulation of cascaded biomass use and elimination of import duties. Also, it is important to develop adequate financing schemes for the adoption of energy efficient and low carbon technologies.

Concerted, long term action by all stakeholders is critical to realise a low carbon and energy efficient future. Governments should help to create a favourable environment that encourages additional gains in efficiency and lowers energy use and emissions, while keeping a strong chemical industry in Europe. Industry should highlight priorities for support, accelerate capital investments as well as research and development, and prompt further focused collaborations with academia and government research laboratories.

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1 Introduction

1.1 The European chemical industry's role in an energy efficient and low carbon society

The European chemical industry is an essential industry manufacturing products used in the majority of everyday goods. The industry adds value to the economy and creates direct employment for 1.2 million people (Cefic, 2012a). Looking towards 2050, the European chemical industry has the potential to continue as an innovative industry contributing to new and currently unknown solutions to fulfil human needs.

The chemical industry uses fossil and renewable resources both as feedstock to make products and as a source of energy to generate heat, steam and electricity. It accounts for roughly one third of the combined energy and feedstock use of the European industry. Its energy and feedstock basis is largely fossil fuel based and as such contributes to the increasing level of greenhouse gases (GHG) in the atmosphere and to climate change. At the same time, the European chemical industry is a vital solution provider to create a more energy efficient and low carbon economy. It contributes to energy efficient solutions in almost all sectors of the economy, and the demand for products of the chemical industry will continue to grow. The challenge for the European chemical industry is to satisfy the demand growth for chemical products with highly efficient European production while reducing carbon dioxide (CO_2) and other GHG emissions.

For this to happen, the European chemical industry needs to be competitive in a global market place, which is challenging due to differences in feedstock and energy prices as well as climate policies and their ambition levels across the world. Globally, energy use continues to increase and to limit the most harmful impacts of climate change on society, global action is required to improve energy efficiency and to transform the energy system towards a lower GHG emissions intensity. Currently, the debate in Europe is focused on how to develop its energy and climate policies in the coming decades given the current absence of a global agreement on GHG emissions reduction and the uncertain outlook on reaching such an agreement in the years to come.

1.2 A contribution to the post-2020 European energy and climate policy debate

Under the auspices of the United Framework Convention on Climate change (UNFCCC), it is agreed to limit global warming to 2 °C, requiring deep reductions in global GHG emissions (IPCC, 2007). The EU

Member States agreed to three targets¹ for 2020 related to energy and climate change, often referred to as the 20 / 20 / 20 package:

- 1. A 20% reduction in GHG² emissions in 2020 compared to 1990 levels
- 2. A 20% share of renewable energy in the EU energy mix in 2020
- 3. 20% energy savings in 2020 compared to projected business as usual levels

At the same time, Europe wants to strengthen its manufacturing base through raising its contribution to the EU's gross domestic product (GDP) to 20% by 2020 (European Commission, 2012a).

In order to keep the global temperature rise below 2 °C, the European Council has agreed on the long term EU objective of reducing GHG emissions by 80–95% by 2050 compared to 1990. Currently, possible routes to reach such a low carbon economy in 2050 and the policy options beyond 2020 are being explored by the European Commission.

In 2011, the European Commission published a roadmap for moving to a competitive low carbon economy ("Low Carbon Economy Roadmap") (European Commission, 2011a). In this document, the European Commission sets out the main elements shaping the EU's climate action to enable Europe to become a competitive low carbon economy by 2050. In the Low Carbon Economy Roadmap, the European Commission explored GHG emission reduction pathways for key sectors with economy-wide reductions in GHG emissions of 79% to 82% by 2050 compared to 1990 levels. Sectoral reductions projected for 2050 range between 42% and 49% for agriculture to almost full decarbonisation for the power sector. For industry, the analyses show that GHG emissions could be reduced by 83% to 87% in 2050. These reductions will be driven by using more advanced resource- and energy-efficient industrial processes, increased recycling, as well as abatement of non- CO_2 GHG emissions.

In the Low Carbon Economy Roadmap, it is acknowledged that continued measures to support the competitiveness of energy intensive and trade exposed industry are required in the absence of global action. The Low Carbon Economy Roadmap explores two options at a high-level: a lower reduction effort for the energy intensive industry, and continued support to compensate for additional costs incurred to the industry (European Commission, 2011a, Chapter 5). It also emphasises that for industry the solutions are sector-specific and the European Commission clearly sees the need to develop specific roadmaps in cooperation with the sectors concerned.

¹ For more background on the 20/20/20 package, reference is made to http://ec.europa.eu/clima/policies/package/index_en.htm

 $^{^{2}}$ Greenhouse gases (GHG) are "gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth's surface, the atmosphere itself, and by clouds," as defined by the IPCC (IPCC, 2007 WGI Glossary). CO₂ emissions are one of the GHG emissions included in the reduction target, with the other emissions being methane, nitrous oxide and fluorinated gases.

Furthermore, the European Commission also published an EU Energy Roadmap 2050 (European Commission, 2011b), to investigate possible scenarios to decarbonise the energy system. The EU Energy Roadmap explores five different decarbonisation scenarios in parallel with two current trend scenarios. In contrast to the Low Carbon Economy Roadmap, the EU Energy Roadmap does not explore scenarios where the EU achieves deep reductions in emissions in 2050 in the absence of global action, and focuses on decarbonisation scenarios where there is global action to meet the 2°C target. Energy related GHG emissions reduction for industry in each of the decarbonisation scenarios is approximately 80% in 2050 as compared to 1990 levels³.

The European chemical industry hereby contributes to the post-2020 energy and climate policy debate by preparing a Roadmap up to 2050, thereby taking a proactive attitude towards key stakeholders. This Roadmap provides, to the extent possible, bottom-up, technologically sound information on the European chemical industry's possible contribution to a low carbon Europe.

1.3 Objectives of this Roadmap

The long term role of the chemical industry as Europe progresses to an energy efficient and low GHG emission future, and the sector's potential to assist Europe in meeting its decarbonisation targets is investigated. The timeline for deploying existing and new technologies from 2020 to 2050 and their potential impact on energy efficiency and GHG emission levels, as well as the competitive position of the European chemical industry is assessed. Cefic commissioned Ecofys to perform analyses and bring forward key conclusions and recommendations from their independent viewpoint, in close collaboration with the sector.

As a strategic orientation for this industry and a high level priority for Cefic's Board, this Roadmap meets the need for the European chemical industry to develop a new, longer term strategic approach to energy and climate policy and contributes to the debate on the post-2020 policy framework. This Roadmap has three main objectives:

- Provide quantitative and more qualitative evidence on the options available to the European chemical industry to contribute to the EU's long term GHG emissions reduction goals. These options apply to technologies and product development for the sector itself and for other sectors of the EU economy.
- 2. Based on this evidence, define a long term vision for the European chemical industry within a European Union that progresses to a low GHG emission future by defining a number of plausible scenarios in the context of global market developments.

³ For a more detailed discussion on the various roadmaps of the European Commission and their relation to each other, reference is made to the website of the European Commission (<u>http://ec.europa.eu/energy/index_en.htm;</u> <u>http://ec.europa.eu/dgs/clima/mission/index_en.htm</u>)</u>

3. Formulate recommendations externally to policy makers and internally to the European chemical industry based on the scenarios studied.

1.4 Roadmap governance and methodology

1.4.1 Project governance

Cefic's Energy, Health, Safety and Environment (HSE) and logistics Programme Council that reports directly to the Cefic board initiated this Roadmap. Day to day management of the project took place via a Roadmap Steering Committee with representatives from national chemical sector organisations and companies. Ecofys performed the analyses and brought forward key conclusions and recommendations, in close collaboration with the sector. Input from the sector was organised via three topic teams with experts from the European chemical industry (Figure 1-1).





In the *topic team Public Policy Review,* the current energy and climate policy situation in Europe was assessed and a comparison was made between the policy burden in Europe compared to the rest of the world (Chapter 3). The *topic team Technology and Innovation* provided key input on the energy efficient and low carbon technologies that are available to the chemical industry and on the applicability of these technologies under the scenario assumptions (Chapters 5 and 7). The *topic team Markets* supported the project by providing input on the development of the demand for and production of chemical products in Europe (Chapter 7) and by defining the scenarios in terms of market developments (Chapter 6).

In the early phases of this Roadmap, four *regional workshops* were organised in Paris (for Western Europe), Milan (for Southern Europe), Warsaw (for Eastern Europe) and Stockholm (for Northern Europe). The aim of the workshops was twofold:

- To inform chemical sector organisations and companies in the respective regions about the objectives of the Roadmap;
- To exchange with the participants on key regional characteristics of the chemical industry and to receive inputs from national or regional initiatives that of relevance in preparing the Roadmap.

The workshops were organised by the national sector organisations of the countries where the workshops took place. The Paris workshop was organised as a joint effort by the German and French sector organisations VCI and UIC. The insights gained in the workshops were used to give regional context to some of the key inputs used for this Roadmap and to some of the key conclusions and recommendations. Reference to these regional workshops is made at several places in this Roadmap.

1.4.2 Roadmap methodology

The approach taken in this Roadmap can be characterised by the following key elements:

- A pan-European approach is taken focusing on the development for the European chemical industry as a whole and not on developments in individual countries or regions. Data for the EU-27 was taken as a basis for the calculations.
- As the context in which the European chemical industry will develop is uncertain, the future of the chemical industry is explored using four scenarios.
- The scenarios differ mainly in three ways: firstly, in their assumptions regarding the energy and climate policy environment in Europe and in the rest of the world; secondly, in their outlook on the development of energy and feedstock prices; and finally with respect to the speed of innovation.
- The scenarios result in four different pathways regarding the development of demand for and production of chemical products in Europe, the development and uptake of energy efficient and low carbon technologies, and the resulting energy use and GHG emission pathways for 2020, 2030 and 2050, using 2010 as the base year of analysis.

- From the scenarios, recommendations are drawn on the conditions required to realise the development and deployment of energy and low carbon technologies while ensuring a healthy and competitive European chemical industry up to 2050.
- In line with the subsector classification normally used by Cefic, five subsectors of the chemical industry are distinguished: Petrochemicals (including intermediates), Basic Inorganics, Polymers, Specialty Chemicals and Consumer Chemicals (see Section 2.1 for more explanation). In addition, cracker products, ammonia, chlorine and nitric acid are studied in more individual detail given their importance in the overall energy and emission profile of the chemical industry in Europe. For the avoidance of doubt, the pharmaceutical industry is not included in this study unless otherwise stated

This Roadmap investigates scope 1 (GHG emissions⁴ in the European chemical industry) and scope 2 (GHG emissions related to the production of purchased electricity and heat) only (Figure 1-2)⁵. Therefore, scope 3 GHG emissions of the European chemical industry are not included⁶. This means that emissions from fossil fuel exploration and production, emissions from the cultivation of biomass (e.g. those related to indirect land-use changes) and emissions related to the end-of-life treatment of chemicals are not included. This choice of scope also implies that an emission factor of zero t CO₂ per unit of biomass used as an energy source or feedstock is used in the calculations (for a further discussion on the overall GHG emission impact of biomass, see Section 5.2.1).

It is important to note that pathway assumptions and conclusions in the time frame nearer 2030 are more firmly based on quantitative analysis than those done for the period after 2030. The projections for 2050 are inevitably more of a qualitative nature and subject to inherent uncertainties. The scenarios developed in this roadmap should not be regarded as precise predictions of the future but as possible routes the European chemical industry could take under certain predefined assumptions regarding economic development, energy prices and the policy landscape.

 $^{^{4}}$ Within this Roadmap CO₂ emissions from the use of fossil fuels and N₂O emissions are taken into account; CO₂ from fossil fuels and N₂O are the two most important GHG emitted by the chemical industry.

⁵ This definition of scope 1 and 2 is in line with the GHG protocol developed by the World Business Council for Sustainable Development (WBCSD), <u>http://www.ghgprotocol.org/</u>

⁶ Defined in the GHG protocol as "other indirect emissions, such as the extraction and production of purchased materials and fuels, transport-related activities in vehicles not owned or controlled by the reporting entity, electricity-related activities (e.g. transport and distribution losses) not covered in Scope 2, outsourced activities, waste disposal, etc." (http://www.ghgprotocol.org/)



Figure 1-2 Summary of the scope of assessment in this Roadmap

1.5 Overview of this Roadmap

Chapter 2 provides an overview of the European chemical industry, while Chapter 3 describes the current policy landscape for the European chemical industry. Chapter 4 focuses on the European chemical industry as an enabler of energy efficiency and emissions reduction for sectors across the economy. In Chapter 5, the energy efficiency and GHG emission abatement options that are available now and in the future are described. The four scenarios are described in Chapter 6, followed by Chapters 7 and 8 that provide the results of the scenarios, and explore the future of the European chemical industry in terms of production, GHG emissions and differing energy profiles. The final Chapter 9 contains policy recommendations and conclusions.

2 The chemical industry today

2.1 A diverse and essential industry

Products from the chemical industry are present in the majority of everyday goods as detailed in Figure 2-1. The chart shows that the chemical industry underpins virtually all sectors of the economy. The big industrial customers of the chemical industry are the rubber and plastic converting industry, construction, pulp and paper. Nearly two-thirds of chemicals are supplied to EU industrial sectors, including construction. More than one-third of chemicals are supplied to other branches of the EU economy such as agriculture, services and other business activities. The product chains of the Petrochemical industry are given in Figure 2-2 as a further example showing the diversity of product applications of the chemical industry.



Percentage of output consumed by customer sector





Figure 2-2 Chemical products make things happen (APPE, 2012, used with permission)

For the purpose of this Roadmap, the millions of products of the chemical industry are categorised into five key subsectors, which are briefly outlined in Box 2-1.

Box 2-1 Subsectors of the chemical industry

The **Petrochemical** sector produces organic building blocks of the chemical industry, like olefins and other monomers, aromatics, alcohols and other intermediates based on these products.

The **Basic Inorganic** industry is a diverse industry. In this sector, the key inorganic building blocks for the chemical industry are produced. Examples are ammonia which is important for the nitrogenbased fertilizer industry, and chlorine, that is an important raw material for example for poly vinyl chloride (PVC) and other chlorinated compounds.

The **Polymer** industry uses some of the intermediates from the Petrochemical sector to form long polymer chains that can be moulded to a variety of end-products, for example to packaging films, automotive parts or insulation materials.

Specialty Chemicals include products such as paints and inks, crop protection, dyes and pigments. They are produced in small volumes but represent significant value, fulfil a specific function, and are often designed for a particular customer's need.

Consumer Chemicals are sold to end customers, such as soaps and detergents, perfumes and cosmetics.

Petrochemicals, Basic Inorganics and Polymers account for roughly 60% of the EU chemical industry sales with Specialty and Consumer Chemicals representing the remaining 40% (Figure 2-3). Total sales in 2010 (the base year of analysis in this roadmap) were € 491 billion. There are significant regional differences in Europe in terms of product portfolio and the shares of the various subsectors.

The chemical industry directly accounts for 1.1% of total EU GDP. It contributes to the economic performance in many sectors that use the products of the chemical industry to create further value added. The sector directly employs about 1.2 million people in the EU and indirectly (e.g. via service providers and consultants) provides employment to many more (Cefic, 2012a).



Figure 2-3 Chemical production by subsector in billion € sales (Cefic, 2012a)

2.2 The global competitive environment of the European chemical industry

The chemical industry operates in a global market-place. The EU chemical trade surplus in 2010 (the base year of the analyses in this roadmap) was \in 42 billion, with 70% of this surplus resulting from the Specialty and Consumer Chemicals subsectors (Figure 2-4). It should be noted that overall, the trade balance of the EU in 2010 was a deficit of \in 178 billion (Eurostat, 2012a). The most important trade partners outside the EU are the rest of Europe (non-EU) followed by the NAFTA region (North American Free Trade Agreement market) and Asia (excluding China and Japan) accounting for about 80% of total trade flows with countries outside the EU.



Figure 2-4 EU chemical trade surplus by subsector (Cefic, 2012a)

The European chemical industry thus operates in a competitive environment. Production costs such as energy and feedstock costs impact the competitiveness of the sector. The trade position of the more energy intensive subsectors of the chemical industry has weakened in recent years (Figure 2-4 and Figure 2-5). This is in contrast to the historically strong position of the EU chemical industry. Trade developments with the Middle East show that this region increasingly uses its feedstock price advantages and availability. Petroleum and associated gas available in this region are used to develop an integrated chemical industry and further strengthen not only its position in a wide range of basic chemicals, but now also some Specialty Chemicals. The trade position with the USA has weakened in most subsectors. One of the reasons for this is the lower fossil fuel prices in the USA which have been largely induced by the rapid development of unconventional oil and gas, leading to a strong increase in the production of oil and gas. Russia has, until now, been unsuccessful in using its competitive advantages in terms of raw materials for basic chemicals.

Trade analysis 2010 versus 2005	USA	Japan	Brazil	Russia	India	China	South Korea	Middle East	Rest of Asia	Extra- EU
Petrochemicals										
Basic Inorganics										
Polymers										
Specialty Chemicals										
Consumer Chemicals										
European chemical industry										

Trade analysis 2011 versus 2010	USA	Japan	Brazil	Russia	India	China	South Korea	Middle East	Rest of Asia	Extra- EU
Petrochemicals										
Basic Inorganics										
Polymers										
Specialty Chemicals										
Consumer Chemicals										
European chemical industry										

EU has a trade surplus and its healthy competitive position improved

EU has a trade surplus but its positive competitive position weakened

EU has a trade deficit but its weak competitive position improved

EU has a trade deficit and its competitive position weakened

Figure 2-5 Extra-EU trade position – analysis of changes between 2005 and 2010 and between 2010 and 2011 (Cefic, 2012a)⁷

⁷ An improved competitive position means that the trade surplus (in %) has increased between 2005 and 2010 or 2010 and 2011 (green colour) or that the trade deficit has become smaller (blue colour).

2.3 Past achievements in energy efficiency and GHG emissions reduction

Energy efficiency has always been high on the agenda of the European chemical sector given the importance of energy costs. Between 1990 and 2010, energy consumption fell by 20% while production climbed 70% in the same period (Figure 2-6, production index based on value in constant prices)⁸. This has resulted in an energy intensity decrease (energy use divided by the production index) of more than 50% (Cefic, 2012a). Reductions of energy intensity were delivered by improvements in energy efficiency, such as the implementation of combined heat and power as an efficient way to meet the electricity and heat demand of the chemical industry, as well as by continuous process improvements. It should be noted that the steep decline observed can also be partly caused by structural changes within the chemical industry (i.e. a shift to higher value added, lower energy intensive products) and by the use of a value based (albeit inflation corrected) index which is sensitive to elements such as profit margins.



Figure 2-6 Development of chemical production (production index based on value in constant prices), energy consumption and energy intensity (indexed, 1990 = 100, Cefic, 2012a)

⁸ All data in this Section is given for the European chemical industry including pharmaceuticals

Despite substantial increase of 70% in production, GHG emissions have been halved since 1990 (Figure 2-7). The reduction in GHG emissions exceeds the decline in energy use as a result of shifts in the fuel mix towards less carbon intensive fuels (lowering GHG emissions, but not the energy use as such) and also because of a decline in process emissions. N_2O emissions in the chemical industry were, for example, significantly reduced by the opt-in in of various nitric acid plants into the second phase of the EU emissions trading system (2008–2012), a reduction which is projected to continue in the years to come (Chapter 7).



Figure 2-7 Development of chemicals production (production index based on value in constant prices) and GHG emissions (indexed, 1990 = 100, Cefic, 2012a)

2.4 Energy use in the European chemical industry

In the chemical industry, both fossil fuels and biomass are used for a wide variety of applications. An important distinction is the use of these materials for feedstock and energy purposes. Fossil fuels and biomass can be used for energy purposes, for instance to generate heat or power which drive compressors and pumps. Furthermore, fossil fuels and biomass can also be used as feedstock to create products.

GHG emissions are released when fossil fuels are used for energy purposes. However, when fossil fuels (such as natural gas and / or naphtha) are used as feedstock to make products, the carbon is in many cases embedded in the product. For example naphtha is used as a feedstock to produce ethylene (C_2H_4), which is polymerised to create polymer products. The carbon content then ends up in the polymer products. For the avoidance of doubt, the GHG emissions related to the end-of-life treatment of these products when this carbon is released (e.g. energy recovery) are not included in the scope of this Roadmap (Section 1.4).

In 2010, the total final energy use in European chemical industry amounted to approximately 3,000 Peta Joule (PJ), and total feedstock was about 2,100 PJ as shown in Figure 2-8. The combined total energy use, including feedstock, is approximately one third of the total industrial energy use in Europe.



Figure 2-8 Feedstock and energy use by the European chemical industry in 2010⁹

The bulk of the feedstock and energy use in the chemical industry can be allocated to a limited number of key production processes (Neelis et al., 2007; Saygin, 2012). The steam cracker process to produce the building blocks of the Petrochemical industry, the production of ammonia (the key building block for the fertiliser industry) and the production of chlorine are together responsible for

⁹ Ecofys analysis based on IEA (2012a), Saygin (2012). Fuel use includes fuel use in boilers and heat related input into combined heat and power installations. Feedstock use is corrected for backflows to refineries using expert judgments on the energy balance of the cracker products production.

approximately one third of energy use (excluding feedstock use) and are studied at the product level in this Roadmap.

The energy use by subsectors is shown in Figure 2-9, which shows that the Petrochemical and Basic Inorganics subsectors consume most energy. In addition to the oil and gas feedstock use given by subsector in Figure 2-9, biomass is used as feedstock as well. It is difficult to find reliable data on biomass used as feedstock, which was estimated at 110 PJ for 2010 based on expert judgments within the topic team Technology and Innovation. Given the uncertainty in this estimate, it is not allocated to individual subsectors and therefore omitted from Figure 2-9.

Dividing the energy use over the sales by subsector yields the energy intensity overview given in Figure 2-10 and Figure 2-11. There is inherent inaccuracy in the (subsector) energy data for the chemical industry (see e.g. Neelis et al., 2007). This is due to the complexity of the chemical industry, the use of fossil fuels and biomass as feedstock and for energy purposes, and the fact that several companies produce products that belong to different subsectors, In Chapter 9 it is recommended to continue the efforts towards better quality data for the chemical industry.



Figure 2-9 Final energy consumption per chemical industry subsector, 2010¹⁰

¹⁰ Source: Ecofys analysis based on IEA (2012a), Saygin (2012), and Eurostat (2007). Final fuel use includes fuel use in boilers and heat related input into combined heat and power installations assuming a 90% reference efficiency for heat production in line with the energy efficiency directive (European Commission, 2012c) and natural gas as fuel. Only feedstock use of energy is shown and feedstock use of chemical upstream products is not shown. For example petrochemical products such as ethylene have energy content and are used as a feedstock to produce Polymers, but are not shown in this figure. Bio-based feed is not shown, because it cannot be attributed to subsectors with sufficient accuracy.



Figure 2-10 Energy use per unit of sales of the five chemical industry subsectors in 2010¹¹



Figure 2-11 Energy costs as a proportion of sales for the five subsectors of the chemical industry subsectors in 2010¹²

¹¹ Ecofys analysis based on ChemData (2012), IEA (2012a), Saygin (2012), and Eurostat (2007). Final fuel use includes fuel use in boilers and heat related input into combined heat and power installations. Use of energy carriers as feedstock is excluded.

The energy intensity overview in Figure 2-11 clearly highlights the high energy intensity of the subsectors producing basic chemicals as compared to the Specialty and Consumer Chemicals subsectors.

Based on the final energy use figures, the CO_2 emissions from combustion, i.e. heat generation in the chemical industry are estimated to be 132 Mt CO_2 in 2010¹³. In addition, process emissions including N₂O emissions from nitric acid and other chemicals amounted to 43 Mt CO_2 e in 2010. Furthermore, the indirect CO_2 emissions associated with power consumption totalled 59 Mt CO_2 , making the total footprint of own emissions and purchased electricity of the European chemical industry 235 Mt CO_2 . The CO_2 emissions for power consumption were calculated in line with the electricity scenarios from the EU energy roadmap. Therefore, an emission factor for electricity of 310 t CO_2 / TWh is used for the calculation of indirect emissions from electricity. The emissions from the EU chemical industry were about 5% of the total EU GHG emissions in 2010.



Figure 2-12 Overview of GHG emissions from the European chemical industry in 2010

The energy and emission profile for 2010 as shown above forms the base year data for this Roadmap. In line with the scope demarcation given in Section 1.4, energy use and emissions outside the boundary of the chemical industry are not part of the quantitative assessment.

¹² See previous footnote for an overview of sources used.

 $^{^{13}}$ Using emission factors of 56.1 t CO₂ / TJ for gas, and 94.6 t CO₂ / TJ for coal in line with the IPPC guidelines for national GHG inventories (IPCC, 2006). For oil products, the emission factor of natural gas is used to reflect that the majority of the oil product use relate to by-products from e.g. the steam cracker process that have an emission factor that is closer to that of natural gas than to that of standard oil products.
3 Comparing policy frameworks

3.1 Operating in a complex policy environment

Major economies have their own individual frameworks for energy and climate policies. As a result, today's international energy and climate policy landscape is fragmented and diverse. This fragmentation is caused by strategic, historical and geological circumstances as well as political choices such as different levels of ambition and the type of policy instruments chosen. This global diversity determines the energy and manufacturing cost dynamics in Europe, which in turn influence the relative competitiveness of the European chemical industry.

Europe's dependence on fossil energy imports is increasing due to diminishing own resources. If the relative energy resource disadvantages and differentials in terms of policy costs increase between Europe and the rest of the world, the competitiveness of the European industry will be affected. However, Europe is surrounded by resourceful energy supply regions and can actively develop its external relations as major global customer and diversify supply. Moreover, Europe can also introduce policies stimulating domestic supply (e.g. renewables, unconventional energy sources).

3.2 The EU policy landscape

The EU has outlined its ambition to reduce the environmental impact of European economic activities. The EU has translated its renewable energy, energy saving and GHG emission reduction targets for 2020 into legislation to ensure the achievement of the targets. Targets and policy tools overlap to some extent and interact with each other. Depending on the policy instruments, Member States can have a significant freedom in the implementation of European legislation. The role and actions of Member States are therefore decisive in many fields of energy and climate policy. As a result, despite common European legislation, comparable conditions for economic actors are not automatically created in different Member States, and the impact and cost-effectiveness of a given policy often varies between Member States.

Table 3-1 gives an overview of the EU energy and climate policies affecting the European chemical industry. The policies with most impact on the chemical industry are the following:

EU emissions trading system

Emissions trading is a tool to achieve an agreed emissions reduction cost-effectively. The carbon market price for CO_2 allowances is being determined by supply (defined by the emissions cap) and demand of companies that decide their own strategies how best (at lowest cost) to reduce GHG emissions. In the EU emissions trading system (ETS), companies within the EU ETS scope need to

surrender allowances for every tonne of GHG they emit. The EU ETS started with free allocation primarily based on historical emissions, which differed per Member State in phase 1 (2005–2007) and phase 2 (2008–2012). In phase 3 of the EU ETS (2013-2020), the methodology for free allocation of allowances is harmonised across Europe. All allowances for electricity generation will be auctioned, and free allocation of allowances will be benchmark-based for industry. The harmonised system of free allocation of allowances and the creation of industry benchmarks rather than free allocation based on historical emissions are important steps forward. However, other (competing) national and EU policies such as energy efficiency policies and renewable energy policies may reduce the demand for CO_2 allowances. This in turn pushes downward the carbon market CO_2 price, but can result in higher overall costs.

The allocation method with benchmarks is still ex-ante fixed, meaning that allocation of free allowances is based on historical production data. The present EU ETS rules with ex-ante free allocation for direct emissions lead to two problems: (1) over-allocation during economic recession and (2) under-allocation in times of economic recovery posing barriers for growth. The over-allocation due to recession became a central point of debate. The European Commission (2012a) stresses that measures are urgent. In the Carbon Market Report (European Commission, 2012b), six non-exhaustive options for structural measures are identified. As set out in their response to this document (Cefic, 2013), the European chemical industry is opposed to short-term market interventions in the trading period before 2020, but rather supports structural improvements for the longer term.

Problems with potential under-allocation directly affect competitiveness and increase the risk and likelihood of carbon leakage. Carbon leakage is a complex issue with various mechanisms (see also Section 7.2). Carbon leakage is defined as emissions displaced as a result of asymmetric climate policy (e.g. Reinaud, 2008) and creates loopholes in environmental policy. Various forms of carbon leakage can be distinguished (Dröge, 2009), including production carbon leakage and investment carbon leakage. Production carbon leakage occurs if production in Europe is more expensive than elsewhere; investment carbon leakage occurs when the expected overall return on investment in Europe is lower than in other parts of the world. If for example a production shift takes place representing 10 Mt CO_2 in the EU to non-capped manufacturing plants outside the EU with the same carbon efficiency (thus creating 10 Mt CO_2 because the intended reduction did not take place. The environmental loss is 10 Mt CO_2 because the intended reduction did not take place. The fuel mix is more GHG emissions intensive.

Barriers and risks for growth under the present EU ETS allocation rules were investigated in Schyns et al. (2012). These barriers and risks can cause investment carbon leakage. A possible way to make industrial growth possible is through the new entrants' reserve (NER). However, the chemical industry is concerned about the legal and operational uncertainties around the (long term) existence of the NER and the access to the NER (e.g. for growth through debottlenecking). A possible solution, proposed by the chemical and other manufacturing industry, is to introduce ex-post benchmark

based allocation, which reflects actual production levels (Alliance, 2007; Ecofys, 2008; Alliance, 2011; Cefic, 2012b).

The free allocation of allowances in phase 3 is based on the stringent top 10% benchmarks (average of the 10% best installations in the EU), which causes 95% of installations to have a shortage against the benchmarks.

Furthermore, the application of the cross-sectorial correction factor (CSF) increases the shortage. This shortage does take away financial resources from many entities that need to invest in low carbon technologies to reach benchmark levels. Although to some extent inherent to a benchmark based free allocation methodology, the allocation could have taken into account the time required to reach the benchmark emission level by taking a less stringent benchmark, an opinion given at some of the regional workshops (Section 1.4).

In addition to the direct costs, there are indirect costs passed on by the electricity providers through end-user electricity prices. Member States are allowed to grant financial compensation for the increase in electricity prices due to the ETS. This compensation, however, is likely to be inconsistent throughout Europe and unpredictable for industry. The regional workshops made clear that many Member States do not plan to offer financial compensation, resulting in an uneven playing field across Europe.

Due to the currently low CO_2 prices in the EU ETS, the total costs for the industry are limited at present, but uncertainties around future costs remain an important concern for the chemical industry in the European Union. The current design of the EU ETS can cause a direct loss of investments due to the barriers for growth as explained above.

Renewable energy policies

Access and availability of renewable energy sources as well as national policies are varying widely across Europe, both in terms of stringency and cost implications. Renewable energy support policies have an increasing impact on consumer end-user electricity prices. Policy instruments that pass on the costs of renewable electricity support to electricity consumers have a direct impact on the costs of industry, on top of the ETS related costs. In some countries there is a significant cost pass-through to parts of the industry. However, large energy users are, in several other countries, (partly) exempted from paying for the costs of renewable energy support. In other countries, the costs are not passed through to final energy consumers but born by public budgets. In some countries, the costs can be relatively high, while in other countries, the costs are still moderate. These differences in policy design, exemptions and cost pass-through result in a non-transparent and uneven playing field in Europe and can be an extra driver for carbon and investment leakage. In several of the regional workshops organised in the context of this Roadmap (Section 1.4), this issue came back (Box 3-1).

Box 3-1 Cost implication of renewable electricity support differs from country to country

Many Member States cover the costs for renewable energy support via levies on the end-user electricity prices. The total costs for renewable energy support is expected to nearly double by 2020, leading to an estimated cost level of about $15 \in /$ MWh, if the additional costs are averaged over all electricity consumed in the European Union (RE-Shaping, 2012). The regional workshops organised in the context of this Roadmap (Section 1.4) made apparent that the cost burden to industry related to these levies differ from country to country and also between subsectors of the chemical industry. In both Germany and Italy, energy intensive consumers are exempted from the often significant renewable electricity support levies for competitiveness reasons. However, the levies result in high cost burdens for less energy intensive small and medium size chemical industries, causing competitiveness problems for those industries. These observations from the regional workshops are an important basis for the recommendation in Chapter 9 to better coordinate renewable electricity support across Europe.

The costs arise from two main sources: (1) subsidies for the generation of renewable electricity, for example in the form of feed-in tariffs or costs to comply with renewable energy obligations, and (2) costs for balancing the system due to the intermittent nature of sources like wind and solar power. The costs for balancing the system are still relatively moderate but are likely to increase in the future as the proportion of renewables grows. The most important options to integrate large amounts of renewable electricity into the power system are better utilisation of existing grids, grid expansion, including international interconnections, demand response management by industry and small consumers, and storage systems, like pumped storage.

Given the rising costs for the chemical industry of renewable energy policies and the accompanying infrastructural needs, the chemical industry is concerned that exemptions from the cost pass-through to energy intensive industries can come under pressure, at least in the public debate. So far, the chemical industry has mostly been exempted from renewable energy levies. Passing through substantial parts of the total costs will, however, have significant impact on the more electricity-intensive companies in the chemical industry.

Energy efficiency

The effect of the Energy Efficiency Directive on energy costs and energy savings is still uncertain as it depends largely on national implementation. It could somewhat level the playing field in Europe by creating similar framework conditions in all Member States, as a joint ambition is formulated. But there may still be substantial differences in the way the directive is implemented in terms of sectoral coverage, policy tools, and effective ambition. In the directive, initial differences between industries are not taken into account, at least not formally.

It is important to make a clear distinction between absolute energy saving ambitions with a total cap on energy use, which result in absolute energy savings targets, and more relative energy efficiency targets, which focus on reducing the energy intensity per unit of output. Product specific energy efficiency improvements are a clear contribution to sustainable and efficient growth, whereas overarching efficiency targets may lead to a product shift instead of physical efficiency improvements and absolute targets could even hamper growth. The findings of this Roadmap make clear (see Chapter 7) that deep GHG emission reduction in the European chemical industry can imply an absolute increase in energy use.

It should be noted that while there is a global agreement that greenhouse gas emission must be reduced, achieving absolute energy savings is not self-evident. The environmental impact of energy consumption strongly depends on the type of energy used. The use of renewable energy is today mainly restricted by costs, but the available potential is huge and exceeds the total energy needs of mankind.

The Directive provides incentives to improve, for example, the energy efficiency of buildings, which leads to more demand for energy-saving products from the chemical industry. Furthermore, if companies identify further opportunities for energy and cost savings, the directive could improve the competitiveness of industry. However, energy saving obligations will also incur costs to consumers and industry (e.g. mandatory savings, voluntary agreements, audits etc.). There is a risk that the costs of energy efficiency obligation schemes are passed through and thus increase energy end-user prices. Badly designed instruments can significantly increase administrative burden to industry.

Both energy savings and energy efficiency targets may lead to a situation where resulting GHG emission reduction is not achieved in the most cost-effective way. In addition, there can be conflicting objectives. For example, the application of carbon capture and storage to achieve GHG emissions reduction requires additional energy use.

Energy Taxation

The current European Energy Taxation Directive prescribes minimum taxation levels for energy consumers. A review currently in preparation, introduces alongside the energy component, a CO_2 component in the taxation for industries and other consumers not subject to the ETS. This could help to share the responsibility of mitigating climate change across all sectors in society and avoid a too narrow focus on the ETS sectors only. The fact that the Directive poses minimum taxation levels to some extent reduces the differences between Member States. There are currently significant differences between Member States in the tax levels to industry and the exemptions granted, which results in an uneven playing field between Member States. Furthermore, there is uncertainty about future exemption of ETS sectors for the CO_2 part and the tax level for the energy part for industries competing globally.

Research and innovation policy

European research cooperation and public private partnerships (PPP) increase the likelihood of scientific breakthroughs and can thus potentially strengthen the competitive position of the chemical industry. Some support for research and innovation is provided at EU level. However, EU research programmes are heavily regulated. Risk taking is not encouraged since funding is largely dependent on the process and less on results. Furthermore, European research policy is not sufficiently complemented with strong support for the development and application of innovative products and processes. The major part of European public research and innovation spending is provided by national research programmes. These national programmes are insufficiently coordinated with each other and national funding programmes are in most cases not open for participation of research entities from other Member States. A European research area that allows the free movement of ideas and researchers, thus increasing the efficiency of European research and development, remains a work in progress.

Consolidated European energy strategy and enhanced infrastructures

Energy mixes and energy sourcing strategies remain under the control of Member States resulting in a variety of energy sources (ranging from nuclear to geothermal) and costs. A full integration of the European electricity and gas markets has not yet been achieved. This is due to a lack of competition, and the challenges in ensuring cost-efficient use and access to infrastructures. Existing national and EU policies interfere with each other. Europe's way towards reliable, globally competitive and environmentally sound energy sources requires functioning markets, coordination and consistency. The EU Energy Roadmap initiative provides further perspectives as a contribution to the on-going policy debate.

Summary

Regarding the overall EU policy framework, an important finding is that there is a lot of overlap between the various policy instruments, leading to a sub-optimal design of the total policy package. It can be concluded that there is—already at the EU level— a large differentiation in policies across the European Union. Most policies are implemented at the national level, the EU ETS being the clearest exception. Impact on the industry varies from subsector to subsector and from company to company, and may be both positive and negative. The balance seems to be that the total package of policies has led to higher costs for the industry, notably due to the introduction of the EU ETS and energy price charges related to renewable energy and other policies.

It is essential that the energy and climate policy framework in the EU stimulates sustainable and efficient growth. The current package, as summarised above, contains a number of elements that pose a threat to the competitiveness of the European chemical industry and could hamper the necessary investments needed towards an energy efficient and low carbon Europe. In Chapter 9,

recommendations are formulated to improve the policy package beyond 2020 to support sustainable growth.

Directive	Role of EU	Role of Member States	Examples of impacts on chemical industry
Renewable Energy			
Renewable Energy Directive	Setting targets for the share of renewable energy	Developing policies for implementation	Supply of renewable energy; increasing electricity prices if Member States pass cost of technology support and infrastructure costs through to industry. Increased sales of products used in renewable energy equipment.
Emissions			
ETS Directive	Setting emission caps, market to trade allowances and defining rules	Limited	Puts price on direct CO ₂ emissions resulting in an incentive for energy efficiency; impacts power prices (indirect costs); risk of carbon leakage

Table 3-1Role of the EU and Member States in different fields of energy and climate
policy

Table 3-1Role of the EU and Member States in different fields of energy and climate
policy (continued)

Directive	Role of EU	Role of Member States	Examples of impacts on chemical industry
Energy efficiency			
Energy Efficiency Directive	Target and framework setting	Developing policies for implementation	May lead to energy cost savings but also to transaction costs; unlikely that Directive leads to efficiency improvement in highly energy-intensive industry. May lead to higher energy costs needed for financing energy efficiency obligations. Can improve the need for energy efficient solutions delivered by the chemical industry
Ecodesign Directive	Defining requirements for energy using products	Implementing and enforcing requirements	Sets standards for specified new equipment (e.g. electric motors) Creates a market for materials for energy- efficient products
Product labelling	Setting framework for EU wide labelling (e.g. for electric appliances)	Enforcement / market surveillance Designing and implementing additional labels at national level, if applicable	Has the potential to change the market for energy- efficient products; the potential is currently not depleted
Environmental performance of buildings	Setting framework and defining requirements	Designing policies for implementation	Creates a market for efficient products and materials

Table 3-1Role of the EU and Member States in different fields of energy and climate
policy (continued)

Directive	Role of EU	Role of Member States	Examples of impacts on chemical industry
Innovation			
R&D subsidies	Defining EU framework programmes Coordinating national efforts	National research programmes	Supports innovation and strengthens international competitiveness of European industry
Others			
Energy market integration	Regulation, coordination	Opening up of national markets, deregulation	Can potentially lead to relative energy price decreases
Minimum energy taxation	Setting minimum levels	Defining taxation levels and, if applicable, exemptions	Increased cost of energy use; impact strongly dependent on level of taxation chosen by Member State

3.3 The global policy landscape

At the UN Climate Change conference in Durban, negotiations with a number of developing countries led to an agreement that, if fully implemented, could have positive environmental and economic impacts. The "Durban Platform for Extended Action" creates a roadmap that should lead (when agreed by 2015 and binding by 2020) to "an agreed outcome with legal force" that will for the first time cover all major emitting economies, including the EU, USA, China, India, etc.

Cefic has long advocated the establishment of a global agreement including all major economies to level the playing field for EU companies that are exposed to carbon costs resulting from unilateral climate policy action. The Durban Platform is a start towards setting the scene for an international agreement on GHG emissions reduction. However, progress towards establishing a strong level playing field with other developed and developing countries (OECD and non-OECD countries) remains slow.

Despite the fact that no international long term agreement is in place, many countries have already implemented policies. Several countries have also implemented energy and climate policies affecting the manufacturing industry, and the chemical industry in particular. Such policies as implemented in major economies, like the USA, Japan, China and India have been studied in the context of this Roadmap. An overview of major policies instruments in these countries is given in Table 3-2.

Table 3-2Major policies impacting the chemical industry in some of the major
competing economies

Country	Major policies	Brief description
China	Top 10,000 programme	Mandatory energy efficiency targets for the enterprises with energy use more than approximately 0.3 PJ
	Differential energy prices	Higher energy prices for companies with energy consumption above industry average
India	Perform-Achieve-Trade scheme	Specific energy consumption targets for 8 industrial sectors. Possibility to trade energy saving certificates
Japan	Energy efficiency benchmarks	Mandatory energy efficiency targets based on best performing companies (top 10–20%)
	Energy efficiency adoption subsidies	Economy-wide subsidy scheme
USA	Best Available Control Technology	Requires pre-constructing permits prescribing maximum specific GHG emissions
	Emissions trading systems	Systems for individual states (California) or groups of states. Not all include industry

An exact comparison of these policies is difficult due to different metrics that define targets (e.g. GHG emissions intensity vs. energy intensity vs. energy savings), differences in the initial situation, different base years and economic growth rates. A semi-quantitative estimate of the actual "regional policy costs" is shown in Figure 3-1. The ambition levels and costs in the EU and other major markets have been estimated, taking into account the type of policies, the historic energy intensity, the ambition level of the target, and the cost allocation. The analysis is based on internal Ecofys sources, also making use of and checking against the limited literature available (ICF, 2012; IIP, 2012; WEC, 2012).

The analysis indicates that the EU has so far shown higher ambition in energy and climate policy than most other world regions resulting in slightly higher costs for industry. It should once more be stressed that there are many, many differences between countries. Therefore, comparisons of ambition levels and costs clearly have an indicative character.

Other countries might follow on Europe's path and become more ambitious in decreasing their environmental footprint, as environmental degradation, social risks, pollution and health impacts increase on their territory. However, when and to what extent the ambition level will be increased in other world regions is uncertain. Therefore, the four scenarios studied differ in the global policy contexts, both in terms of overall stringency (global action versus inaction) and in differentiation between world regions.



Figure 3-1 Policy ambition levels and associated costs in the European Union and in the rest of the world

4 The role of the chemical industry in other sectors' low carbon development

The chemical industry contributes to energy efficiency and GHG emissions reduction in all sectors of the economy through their products, as the examples in Box 4-1 illustrate. This chapter describes and quantifies the avoided GHG emissions¹⁴ of solutions in the current market in which chemical products play an important role. The continuous innovations in products of the chemical industry and their potential future contribution to energy efficiency and GHG emissions reduction will be addressed in Chapter 8.

In recent years, a number of important studies were carried out to quantify the contribution of the products from the chemical industry to avoid GHG emissions from other sectors of the economy. In these studies, the lifecycle GHG emissions of chemical products, including extraction, production, use and disposal are compared with a certain reference case (alternative product or market average). The potential to avoid GHG emissions in the other sectors is most often realised in the use phase, where chemical products contribute to higher energy efficiency (lighting, insulation) or an increase in renewable energy production (solar and wind power). Quantifying avoided GHG emissions is not easy for a number of reasons:

- Defining the reference situation in the absence of the use of the chemical product is not always straightforward. An alternative may exist, but may differ in respect of costs and availability, which influences the comparison.
- Avoided GHG emissions take place over the lifetime of the chemical product. For products
 with long life spans, such as buildings, it is not always easy to estimate future avoided GHG
 emissions. Conditions may change over time, for example the electricity mix and heating
 technology, affecting the amount of avoided GHG emissions. Also, the reference situation is
 dynamic, because alternative products might for example improve their performance as well.
- Avoided GHG emissions are often achieved by joint action of various actors and products in the value chain. There is no consensus yet on how to allocate these savings between the various participants.

¹⁴ Avoided GHG emissions can be defined in this context as the additional GHG emissions that would take place if an alternative solution (in which chemical products do not play a role) were applied instead of the solution in which chemical products does play an important role.

Box 4-1 Examples of contributing chemicals to key sectors of the economy

Buildings – **insulation.** Insulation of buildings is probably one of the most well-known chemical applications to avoid emissions. Plastic insulation materials such as expanded polystyrene (EPS), extruded polystyrene (XPS) and polyurethane (PU) have excellent insulation properties and a broad applicability resulting in high energy savings from home heating and cooling and related CO₂ savings.

Transport – light-weight automotive parts. The use of polymers and composite materials (e.g. glass and carbon fibre reinforced plastics) in the automotive industry substitutes materials like steel, aluminium and glass, reducing the weight of vehicles. A reduced weight results in less fuel consumption per driven kilometre and reduces CO₂ emissions accordingly.

Domestic consumption – lighting. Incandescent light bulbs are gradually replaced by compact fluorescent lamps (CFL) or light emitting diodes (LED). The chemical industry produces fluorescent and diode materials which convert energy to visible light. CFLs and LEDs have a four times higher luminous efficiency than incandescent lamps, resulting in reduced electricity use and CO₂ emissions.

Agriculture – fertilizer and crop protection. The use of chemically synthesised inorganic fertilizers (nitrate fertilisers, phosphorus and potassium) and crop protection (pesticide) increase the yield per area of land considerably. This means that less land (mainly forests) needs to be converted to crop land, avoiding the release of CO_2 to the atmosphere. With an expected increase in the world population in the coming decades, this chemical application can help to avoid large amounts of GHG emissions.

Power – solar power. Trichlorosilane is the key intermediate compound used to produce highpurity silicon, which is applied in solar cells as a semi-conductor. No non-chemical alternatives exist for this application. Therefore, the chemical industry is an essential part of the value chain leading to the generation of solar power, thereby substituting electricity production based on fossil fuels.

The International Council of Chemical Associations (ICCA) commissioned in 2009 a study to quantify the GHG emissions reduction enabled by the chemical sector worldwide (ICCA, 2009). This study compares the GHG emissions of a chemical product in a specific application over its lifetime with the next best non-chemical alternative. The study calculates GHG emissions for 102 individual chemical product applications in the year 2005 and 2030. Emission abatement is expressed through two metrics. The first is a gross savings (or X : 1) ratio, where the amount of avoided GHG emissions through the use of a chemical product is measured against the amount of GHG emissions during that product's entire life cycle. The second metric is the net avoided GHG emissions, which represents the difference between the gross avoided GHG emissions by its use and the GHG emissions during that product's entire life cycle. The ICCA study identifies a number of applications as the most important contributors of avoided emissions, including insulation, fertilizers, lighting, packaging, and marine

antifouling. The ICCA study reports net avoided emissions of 3.6 to 5.2 Gt CO_2 equivalents at global level for 2005.

PlasticsEurope commissioned a study to quantify the impact of plastics on life cycle energy consumption and GHG emissions in Europe (EU-27 plus Norway and Switzerland, Pilz et al., 2010). The study compares plastics to the mix of alternative materials available on the market, such as metals, glass and cardboard, across the total life cycle. The energy savings and avoided GHG emissions are based on a theoretical substitution of plastics by alternative materials. The alternative material selected depends on the application. In the use phase the calculation covers situations where plastic products have a different impact on energy and GHG emissions compared to alternative products. The study calculates the avoided emissions in other sectors for 32 applications in the year 2007. The study reports that the substitution of plastic products throughout Europe (EU 27 + Norway and Switzerland) by other material, where possible, would increase the life cycle energy consumption by 57% and would cause 61% more GHG emissions.

Under the leadership of ICCA and the World Business Council for Sustainable Development (WBCSD), a harmonised methodology for avoided GHG emission accounting is currently under development. This method will address the difficulties as the ones mentioned earlier in this chapter and will provide clear guidelines. At present, however, no widely accepted method for accounting and reporting of avoided GHG emissions is available.

The ICCA study is considered the best current option to estimate the GHG emission abatement in other sectors, in which chemical products play an important role and is the basis for the estimate of avoided GHG emissions as given below. One adjustment has been made to the ICCA approach to be in line with the WBCSD / ICCA initiative, i.e. avoided GHG emissions have not been allocated among the chemical industry and other partners in the value chain¹⁵. Instead reported avoided GHG emissions represent the GHG emissions avoided along the complete value chain.

By using the methodology of the ICCA study, in combination with European data, it is estimated that the products manufactured by the European chemical industry in 2010 contribute to over 1.5 Gt CO_2e of avoided GHG emissions during their use (Figure 4-1)¹⁶. This is equivalent to roughly 30% of the total European GHG emissions in 2010. Due to the methodological difficulties as outlined above and the related uncertainties in the necessary conversion from the worldwide figures to EU estimates, the figure should be regarded as an order of magnitude estimate only. It has to be noted that the avoided GHG emissions values in Figure 4-1 refer to a complete value chain and as such cannot be

¹⁵ For the assessed products, this is only relevant for wind power.

¹⁶ Due to uncertainties in the data used and different methodologies used in the avoided emissions calculation, it is very possible that other studies arrive at other values. For example, Brandt and Pilz (2011) found avoided emissions for packaging of 61 Mt CO₂ equivalents in 2007.

compared to the emissions of the European chemical industry documented elsewhere in this Roadmap, which is limited to scope 1 and 2 emissions only (Section 1.4)¹⁷.



Figure 4-1 Net avoided GHG emissions for eight selected applications in which chemical products play an important role. Values based on the 2010 European production volumes

¹⁷ For this reason, the ratio between avoided emissions and emissions from the chemical industry following from this Roadmap cannot be compared with the ratio derived in the ICCA study (ICCA, 2009). Also, the avoided GHG emissions have, in this estimate, not been allocated among the chemical industry and other partners in the value chain.

5 Technical options and innovation opportunities for the European chemical industry

5.1 Introduction

The scenarios detailed in Chapter 6 and 7 investigate the deployment of technologies to reduce GHG emissions and increase energy efficiency. This chapter therefore describes these technologies. The chapter is structured following the material and energy flows in the chemical industry, as illustrated in Figure 5-1.

The first group of options relates to the evolution of the feedstock towards a lower use of fossil feedstock, such as the use of bio-based resources, recycled materials and CO_2 as feedstock (Section 5.2).

Further process energy efficiency improvements and improvements to auxiliary processes on chemical sites represent the second group of options (Section 5.3).

The third group applies to heat sources and on-site energy generation options, such as lower carbon fuels and the use of Combined Heat and Power (Section 5.4).

The fourth group of options to reduce GHG emissions is the abatement of N_2O emissions for example from nitric acid production and capturing and storage of CO_2 from process streams and flue gases (Section 5.5).

The manufacture of ammonia, cracker products, chlorine and nitric acid¹⁸ represents such an important share of energy use and GHG emissions that the options available to these products are discussed individually. Data was collected on measures that can be applied to plants operating in 2010 and characteristics of newly built installations in 2020, 2030 and 2050 (Section 5.6).

No attention is paid in this chapter to the reduction of the GHG emissions related to electricity production (one of the options shown in Figure 5-1). This is largely outside the control of the chemical industry. The GHG emission factor for electricity is exogenously assumed in the scenarios studied (Chapter 6).

 $^{^{18}}$ Nitric acid production is taken as a proxy for all chemical processes emitting nitrous oxide (N₂O).



Figure 5-1 Schematic of feedstock and energy flows and associated GHG emissions for the chemical industry and associated opportunities for improvement

Data were collected in line with anti-trust guidelines from both open and classified sources, mostly provided by industry experts. Preference was given to input from industrial experts above literature data. Classified data were treated confidentially and made anonymous when used.

The information given in this chapter is provided independently to the scenarios that are described in Chapter 6. In Chapter 7, the implementation rate of the options described and the choices for new processes are determined using, where possible, an Internal Rate of Return criterion. This applies mainly to the products studied individually. In cases where detailed cost data were not available (which was often the case), a more generic approach was followed to make the scenario projections (see Section 6.5 for more details).

Due to the limited availability of especially the costs data, it is not possible to provide a marginal abatement cost curve for all options described in this chapter. Such a curve would express all options as function of the costs of abated GHG emissions. This is done in for example the McKinsey cost curve work and similar studies (McKinsey, 2009; Ecofys, 2009). To optimise the overarching energy and climate framework, it is necessary to compare the options listed here with abatement options outside the chemical industry. The most cost-efficient way forward for climate protection is to tap those potentials which are cost-efficient even in the absence of a CO_2 price signal.

5.2 Evolution of feedstock

The chemical industry uses both fossil fuels and biomass as feedstock. For Petrochemicals, the feedstock is mainly oil derived (e.g. naphtha used in the steam cracking process), and for Basic Inorganics, natural gas is used for the production of ammonia. The use as feedstock forms a significant part of the use of fossil fuels and biomass in the chemical industry (see Chapter 2). The carbon in the fuel used as feedstock in the Petrochemical industry is embedded in the products via the initial building blocks towards final products. GHG emissions are only released when disposing and combusting the end products. These GHG emissions can be reduced by efficient utilisation of existing feedstock and the use of alternative feedstock. Three options can be distinguished:

- The use of **renewable resources** such as biomass (Section 5.2.1)
- Recycling, i.e. the use of **secondary feedstock** like industrial and post-consumer waste streams (Section 5.2.2)
- The use of **other alternative feedstock** such as the capture and utilisation of CO₂ (Section 5.2.3).

In line with the scope of this Roadmap (refer to Section 1.4), GHG emissions related to the disposal phase of chemical products are not taken into account in the GHG pathways calculated. Paying attention to the use of feedstock is nevertheless important, because the current use of fossil fuels as feedstock represents a significant share of the fossil fuel use in the chemical industry and leads to significant emissions when the products from the chemical industry are combusted. Although not quantitatively assessed in this Roadmap, these emissions are an important part of the life cycle emissions of chemical products. Changes in feedstock use can also lead to changes in energy use (for example, routes using biomass as feedstock can have different energy use) and to changes in the demand for certain chemicals products (for example, recycling can reduce the demand for primary polymers). These changes are taken into account in this Roadmap (Chapter 7).

5.2.1 Bio-based feedstock

From a technical point of view and based on the applications of industrial materials, the potential for substitution of fossil-based materials with their bio-based counterparts is significant (IEA, 2012b). In some cases, the same chemical can be made either via a bio-based route, or via a petrochemical based route. In other cases, new chemicals can be made via a bio-based route, providing alternative carbon sources and potentially new applications. When evaluating the substitution of petrochemical based products with bio-based products, functionality, sustainability impacts and economic viability should be taken into account over the full life cycle – including the production of biomass and total energy use. Currently, the cost of bio-based production exceeds the cost of petrochemical based production in many cases (IEA, 2012b).

There is a multitude of potential bio-based feedstock materials, conversion routes and bio-based products. Figure 5-2 gives an overview of current feedstock types, conversion routes and products based on the classification of bio-refineries made by IEA Bioenergy Task 42 (IEA, 2012b).



Figure 5-2 Bio-based chemicals can be produced from different feedstock, leading to existing products and new products with similar functionality. Taken from IEA (2012b)

Feedstock for bio-based chemicals

Bio-based chemicals can be produced from many types of bio-based feedstock, e.g. starch, sugars, vegetable oils, animal fats or lignocellulosic¹⁹ material. First generation feedstock²⁰ is already

¹⁹ Lignocellulosic woody biomass is composed of cellulose, hemicellulose, and lignin. Lignocellulosic biomass can be grouped into four main categories: agricultural residues (including straw, corn stover stalk and leaf residues, and sugarcane bagasse), dedicated energy crops (like switch and miscanthus grass, eucalyptus etc.), wood residues (including sawmills and paper mill discards), and municipal paper waste.

²⁰ First generation feedstock is typically derived from food commodities that can be converted with conventional technologies (like fermentation and transesterification).

commercially converted into chemicals (see Box 5-1 for an explanation of different generations of biomass). For example, *Coca-Cola* sources bio-ethanol from Brazil to use it in partially bio-based polyethylene terephthalate (PET) bottles²¹. *Danone* introduced a bottle including 20% of polymer from sugar cane waste in 2010. So-called second generation feedstock, such as those based on lignocellulosic biomass, could become technically available in the next 5–10 years²². The first plants demonstrating this technology are now coming into production—albeit with small capacities compared to current steam crackers²³.

Box 5-1 Generations of biomass feedstock

Biomass feedstock is typically divided into three generations. Within the area of biofuels, there is no widely agreed definition of first, second and third generation biofuels. No single, agreed definition exists. In general, the following distinctions can be made:

- First generation bio-based products are made from simple molecules, using existing technologies such as fermentation or transesterification. Sugars and vegetable oils found in arable crops are used as feedstock in these processes.
- Second generation is typically used to describe bio-based products made from (ligno-) cellulosic biomass, such as woody crops or agricultural residues like straw. Typically fermentation is used, but the lignocellulosic material first has to be broken down to simple sugars, which is a more complex process.
- Third generation biomass is used to describe more advanced options that are further from commercialisation, such as algae.

Some sources, however, simply refer to bio-based products as either "first generation" or "advanced". In this case feedstock that is waste and residues would usually be described as "advanced". If the above categorisation is used, waste and residues could be described as either first or second generation, as they include many different potential types of feedstock. Some of them are relatively easy to convert to a usable fuel (e.g. used cooking oil), while others require cellulosic conversion technologies (e.g. straw).

²¹ MEG (mono-ethylene glycol) makes up 30% of the PET by weight, and PTA (purified terephthalic acid) makes up the other 70%. The bio-ethanol from Brazil is used for MEG production, whereas the PTA is still based on fossil sources.

²² Several cellulosic ethanol plants are being built and coming online, albeit with some subsidies. See also (IEA, 2011a).

²³ Cellulosic Biofuels, Industry Progress Report 2012–2013 (AEC, 2012) shows that by 2016 a handful of facilities with a capacity of 25 to 30 million US gallons per year are expected to come into operation. If e.g. these amounts of ethanol were used for ethylene production, this translates into 50 to 60 kt of ethylene per year, which is approximately 10 times smaller than an average steam cracker.

Often, the appropriate bio-feedstock to use depends on the function of the desired product. For example:

- The majority of fatty acid derivatives are used as surface active agents in soap, detergents and personal care products. Their most important sources are coconut, palm and palm kernel oil, which contain many C₁₂ to C₁₈ saturated and mono-unsaturated fatty acids.
- Multiple unsaturated oils such as soybean, sunflower and linseed oil serve the production of alkyd resins, linoleum and epoxidised oils. Rapeseed oil, which is high in oleic acid (unsaturated C₁₈ fatty acid), is used in bio-lubricants. For lubricants and hydraulic fluids, plant oils usually only require minor chemical modification to fully replace fossil oils.

Conversion routes to bio-based chemicals

Biomass feedstock can, according to its molecular structure, be converted using a wide spectrum of technologies to form certain products, such as:

- **Fermentation**, which can convert fermentable sugars into multiple products following metabolic routes. For example, bio-ethanol can be obtained by fermentation of a sucrose-based feedstock such as sugarcane or sugar beet, and from starchy biomass such as corn or wheat by hydrolysis followed by fermentation. These two production routes are well developed and used for production of bio-ethanol as a transport fuel in countries such as Brazil, the USA, Europe and China.
- **Transesterification.** This process has been used to recycle polyesters into individual monomers. It is also used to convert fats (triglycerides) into biodiesel; the triacylglycerol molecule the major component of most plant oils can be split into glycerol and fatty acids, which in turn can be converted into alkyl esters (i.e. biodiesel) via transesterification. Biodiesel has been used to power heavy-duty vehicles for over 50 years.
- Thermo-chemical conversion. (Ligno-)cellulosic biomass, e.g. wood, can be gasified to produce synthesis gas, which can be used as feedstock for the production of ammonia, methanol and other chemicals. The preparation and gasification of biomass makes the overall process complicated, and therefore the investments per tonne of synthesis gas production capacity are about 6 times higher than for conventional routes (i.e. steam methane reforming). To build such a plant in an economical way, a large feedstock price difference is needed (i.e. cheap woody biomass and / or expensive natural gas). Additionally, transportation and handling of biomass, as well as dealing with by-products such as ashes, should be taken into account. Large-scale biomass gasification is technologically challenging; however, recently a cellulose gasification demonstration project for the production of biomass and set than of biomass.

²⁴ The Woodspirit project was awarded the grant under the NER300 scheme. NER300 is a funding programme for innovative projects for environmentally-friendly CO₂ storage and renewable energy.

within the NER300 programme. This project aims to develop a 900 kt per year demonstration methanol production facility, aimed to be operational by 2015 (Voegele, 2011).

• **Pyrolysis** is the thermal depolymerisation of biomass at modest temperatures in the absence of oxygen. Biomass can be converted into a liquid pyrolysis product²⁵. The so-called pyrolysis oil, which consists of a broad range of different molecules, can be fractionated into various high and low value products. The first challenge is to steer the pyrolysis process in such a manner that the desired products are obtained. The second challenge is to design the process in an economically competitive way.

Bio-based chemical products

Currently, a wide spectrum of bio-based chemical products already exist, such as engineered polymers and fibres, soap and detergents, cosmetics, paints and varnishes, construction materials and lubricants. This shows the wide variety of applications of bio-based chemicals.

Bio-based building blocks that are identical to their petrochemical equivalents (e.g. ethylene from methanol or ethanol) can be used in the same way as fossil-based building blocks to produce a wide range of end products ('drop-in solution', the downstream conversion routes can still be used). The extent to which these bio-based products will be used depends on the availability and price of the conventional fossil-based product compared to the bio-based alternative. Examples are:

- **Bio-ethylene** made from bio-ethanol (from biomass) represents a chemically identical alternative to ethylene. In Brazil, bio-ethylene is already produced in a new plant producing 200 kt of ethylene per year (IRENA, 2013). The availability of cheap sugar cane feedstock, and the producers' expectation to be able to get a premium for the bio-polyethylene produced from bio-ethylene, contribute to the economic viability of this project.
- Organic chemicals, produced via fermentation of fermentable sugars such as **lactic acid and propanediol.**
- **Synthesis gas** using a biomass route such as gasification of woody biomass with steam. This is possible in pilot scale, but not proven at larger technical scales yet. The synthesis gas produced can be synthesised to **methanol** using standard methods. Bio-methanol can then be used to produce important building block chemicals like **ethylene and propylene** via methanol-to-olefin routes. Also, the methanol-to-olefins synthesis step starts to be commercially available²⁶.

²⁵ Other products are syngas and biochar (suitable for agricultural use or use as fuel).

²⁶ The Wison (Nanjing) Clean Energy Company Ltd. aims to start up a methanol-to-olefins facility at an existing coal chemical complex in China, projecting 295 ktonnes per annum of ethylene and propylene production. In 2010, a successful start-up of a 600-ktonnes-per-annum plant owned by China Shenhua Coal to Liquid and Chemical Company Ltd. was reported.

Other bio-based chemicals (such as polylactic acid and certain Specialty Chemicals) could substitute existing fossil fuel based chemicals when the bio-based alternatives meet customers' technical requirements. They may also offer new business opportunities due to their unique properties.

Assessment of potential of bio-based feedstock

The future share of bio-based feedstock was estimated based on top-down studies such as the SPIRE Roadmap (SPIRE, 2012), Star-COLIBRI (Star-COLIBRI, 2011a; Star-COLIBRI, 2011b) and company expert input. The products studied individually in this Roadmap were treated separately (refer to Section 5.6).

Polymers represent a large potential for the application of bio-based materials. This Roadmap therefore further elaborates on this group of products. A 2006 study prepared under the European Commission's GROWTH Programme (DG Research) (BREW, 2006) as a result of a collaboration project between academia and industry was used to estimate the potential for biotechnological production of bulk chemicals from renewable resources. The BREW project studied processes which convert biomass-derived feedstock (e.g. fermentable sugar) into organic bulk chemicals (e.g., lactic acid, acetic acid, butanol and ethanol) by means of white biotechnology, i.e. by fermentation or enzymatic conversion, either with or without genetically modified organisms.

In this Roadmap, production of bio-based chemicals is currently assumed to have slightly higher energy consumption than in traditional manufacturing processes. All fuel / heat in the new bio-based routes is assumed to be based on biomass²⁷. In 2050, the energy use of bio-based routes is—in the generic approach that is applied to subsectors—assumed to be on average similar to the energy use of fossil-based routes²⁸. In reality, the energy and GHG emission performance for production of bio-based chemicals will depend very much on the feed used, conversion technologies, and the desired product (see also Box 5-2). Moreover, it is unclear which part of the energy requirements will fall within the scope of the European chemical industry.

In this Roadmap, feedstock-related GHG emissions and other emissions outside the boundaries of the European chemical industry are not quantified. Therefore, assessment of upstream biomass emissions is not relevant for bio-based feedstock. When assessing the sustainability of biomass use—including use as feedstock—it is important to take into account the full life cycle GHG emissions of all forms of biomass. Reference is made to Section 5.4 for more information on this issue.

²⁷ Often, only part of the biomass can be used as feed and residues can be used as source of heat.

²⁸ This is only an order of magnitude estimate, based on cradle-to-factory gate based energy uses in (BREW, 2006). Based on lignocellulosic bio feed, and for several products, the bio-based routes with lowest energy use available in 2005 and in the future (assumed 2025-2035), have been compared to their fossil equivalents.

Box 5-2 Energy and GHG emissions of bio-based chemicals compared to their alternatives

Pilz et al. (2010) shows some examples of the effect of renewable resources on energy and GHG emissions of two types of bio-based plastics:

- Comparing packaging made from PLA and PET. The influence of production conditions (especially energy mix) of PLA products and the influence of waste management options on the results of life-cycle GHG emission comparison is significant. Under current waste management conditions, bottles made from PET have less climate change impact than bottles made from PLA, but depending on the waste management conditions, the results vary significantly.
- Comparing renewable and fossil based polyethylene over their full life cycle. On average low-density polyethylene (LDPE) film derived from renewable resources shows an advantage of 2–3 kg CO₂ per kg LDPE compared to LDPE film based on fossil resources. This benefit can vary considerably depending on the resources used to produce the bio-based ethanol.

The study concludes that some polymers based on renewable resources are not by definition better than conventional plastics based on fossil resources. The range in their overall GHG emission performance (due to feedstock selection and waste options) is much greater than the range of conventional plastics, either due to waste management conditions or resources used in the production of bio-based building blocks. In addition, further decarbonisation of electricity in the future strongly affects the results of these comparisons.

5.2.2 Valorisation of waste: Recycling of plastics

Data on recycling of plastics waste have been collected via open sources and disclosed sources provided within the context of the topic team Technology and Innovation. Assumptions and data have been discussed with and validated by this topic team. The main references used for this Roadmap are Pilz et al. (2010), IEA (2009a), VNCI (2012) and Consultic (2012).

Valorisation of plastic waste streams, residue streams and recovery of end-of-life products takes place around Europe. What is today considered as an industrial waste or post-consumer waste could entirely or mostly be used as feedstock, e.g. part of the raw material mix, by other industrial sectors in 2050 (SPIRE, 2012).

The carbon embedded in polymers ends up in plastic products that ultimately will be disposed of. This valuable resource can be recovered for recycling or for energy recovery. This Roadmap discusses utilising plastic waste by means of mechanical and feedstock recycling and evaluates how much primary polymer production can be replaced by mechanical recycling and how much feedstock can be replaced in the production of chemicals and / or polymers. Energy recovery is outside the scope of this Roadmap, but is another important option to recover energy from plastics-rich waste streams.

PlasticsEurope calls for zero plastics to landfill by 2020 as opposed to the 10 Mt per year of post-consumer plastic waste going to landfill today. This entails stimulating high-quality recycling and extended collection of post-consumer plastics as well as the use of efficient energy recovery for the post-consumer plastic waste that cannot be recycled in a sustainable way.

Figure 5-3 gives an overview of the plastics value chain, including waste management of postconsumer plastics in the EU-27 plus Norway and Switzerland. The share of post-consumer plastic waste that is disposed to landfills is more than 40%, but this share is getting smaller due to regulation and continuous improvement in end-of-life management of plastics. About 60% of the post-consumer waste is recovered, of which 60% is used for energy recovery.



Figure 5-3 Recovery of post-consumer plastics in the European Union (+ Norway and Switzerland) in 2010 (PlasticsEurope, 2011)

About one quarter of the collected post-consumer waste are currently recycled either by mechanical recycling or feedstock recycling.

Three options for recycling of polymers are distinguished in this Roadmap:

- 1. **Back to polymer (=mechanical recycling)**: Collection and mechanically processing of waste plastics to produce recycled polymers.
- 2. **Back to monomer (=feedstock recycling)**: Breaking down certain polymers into their monomers by means of a chemical process.
- Back to feedstock (=feedstock recycling): Breaking down polymers into hydrocarbons or a mixture of carbon monoxide and hydrogen by means of a thermal process.

Back-to-polymer techniques, usually referred to as mechanical recycling, are recycling techniques that use waste plastics for the manufacturing of new plastic products without breaking down the polymers. This method is especially applicable to post-industrial waste, which is generated either in the production of polymers or in the plastic conversion industry. Mechanical recycling is also applied to recover several post-consumer waste streams, e.g. PET bottles. For these streams, mechanical recycling involves shredding the used plastics products into flakes, washing and subsequently heating and remoulding into products. The recovery of plastics from heterogeneous waste streams can be increased through improved product design to enable their recovery after use, appropriate consumer labelling, and the use of the Resin Identification Code (RIC) on all plastics. Recycling rates are likely to further increase with improved collection, sorting and identification technologies. The chemical industry can enable the recovery by setting up joint efforts with the plastic converter industry. An example is the Vinyloop process: a solvent extraction based process to recycle PVC polymer. This process claims to cut the process energy demand by 46% compared to the production of virgin PVC (Vinyloop, 2012).

Since 2006 the share of post-consumer waste that enters mechanical recycling operations increased from 16% to 25% in 2010 of the collected waste (average for the EU 27 + Switzerland and Norway). A number of countries have total plastic recycling rates above 30%, e.g. Norway, Sweden, Germany and the Netherlands. There are also countries with recycling rates below 20%, among them France, UK, Greece and Finland (PlasticsEurope, 2011). Mechanical recycling is constrained by several factors, such as costs, type of waste collection schemes, the quality of the waste streams and its availability. Furthermore, it competes with other waste valorisation approaches such as incineration with high-efficiency energy recovery (Pilz et al., 2010).

The energy use for mechanical recycling for streams that are easy to collect and clean, such as polyethylene and PET, is in the order of 10-20 GJ / tonne of plastic. This is 25-60% less than the process energy for producing primary polymers²⁹. The reduction can be bigger if feedstock savings are taken into account. Costs for recycling vary widely, from 100 to $1200 \notin$ / tonne, depending on the type of plastic, location, collection scheme and way of processing (ACRR, 2012). Reported market

²⁹ http://www.agentschapnl.nl/content/rekenvoorbeelden-ketenmaatregelen-rubber-lijm-en-kunststofindustrie-mja

prices for recycled plastics depend heavily on the quality of the waste stream. The price of virgin material also impacts the price of recycled material. When comparing prices, the quality and the use of the material that can be substituted have to be taken into account.

Only a minor proportion of the recycled polymers has the quality to substitute primary polymers such as is the case currently for e.g. PET. A study by IEA assumes that recycling leads to polymer substitutes in only one third of the cases, whereas the two-thirds are used for applications for which primary polymers are not used (IEA, 2009a). This substitution of applications for which no primary polymers are used can potentially lead to a reduction of GHG emissions, but this has not been further studied in this Roadmap.

Back-to-monomer or depolymerisation is of particular interest for condensation polymers with a high value, e.g. polymethyl methacrylate (PMMA) (Brems et al., 2012). However, as production volumes of these polymers are often small, they are not treated separately in this Roadmap. Depolymerisation techniques are technically available for e.g. PET and for recycling nylon-6 carpets back to caprolactam. PET can be broken down into monomers and oligomers via various depolymerisation technologies. Although chemical recycling is more expensive than mechanical recycling, the product can directly replace virgin monomers. Current commercially available routes are glycolysis, methanolysis and alkaline hydrolysis (Shen, 2011). The estimated production costs are 25–36% higher than the market price for dimethyl terephthalate (DMT), a monomer for PET, making this route unattractive in economic terms under the future energy price assumptions of this Roadmap (Scheirs and Long, 2003).

Back-to-feedstock techniques turn solid waste plastics into high value feedstock that can be used as raw material for the chemical industry. The structural bonds in the polymers are broken by applying heat, sometimes in combination with a catalyst to facilitate a chemical reaction. Torrefaction, pyrolysis and gasification are possible future processes but need further investigation. Gasification takes place with the controlled addition of oxygen. Plastic waste is partially combusted to yield a gas mainly consisting of CO and H₂, called synthesis gas. Synthesis gas can be used as a fuel but has more commercial value as a feedstock for the production of chemicals (e.g. methanol, ammonia, polymers). Under the assumptions used in this Roadmap, this route is to a limited extent competitive in comparison with steam cracking to produce cracker products (see Section 5.6).

5.2.3 Utilisation of captured carbon as feedstock

Carbon capture and utilisation (CCU) comprises a broad range of processes involving the use of CO₂ in the fabrication or synthesis of products. The assessment of CCU in this Roadmap is based on Parsons Brinckerhoff / GCCSI (2011), Styring et al. (2011), BMBF (2012) and Hanegraaf and Spaans (2012), with additional input from Ecofys experts and the topic team Technology and Innovation.

 CO_2 —as the end product of energy conversion processes—has a much lower energy content compared to most chemicals. Conversion of CO_2 to value-added products requires energy intensive

reduction—with for example H_2 , electricity, or via chemical reactions. When the aim is to avoid emissions of CO_2 the energy required must be produced "carbon-free" to avoid further production of CO_2 to generate the energy required. A prerequisite for building new hydrocarbon structures from CO_2 is thus the availability of cheap excess carbon-free energy. The use for CCU competes with other uses of this competitive carbon-free energy.

For almost all applications in the chemical industry, the CO_2 needs to be available in pure or highly concentrated form, meaning that after capturing the CO_2 needs further treatment and purification. The utilisation of CO_2 (CCU) could be developed in symbiosis with carbon capture and storage (CCS). If investments in pipeline infrastructure required for CCS are made, these could also serve as a feedinfrastructure for CCU applications, while the storage functionality delivered by CCS could ensure optimal use of the CCU-based plants. On the other hand, CCU could potentially accelerate improvements in capturing technologies, increase public acceptance for CCS and be an alternative for CCS in places where storage of CO_2 is not possible.

To describe the future potential of CCU as a feedstock for the chemical industry, a distinction can be made between:

- 1. Processes or products where the CO_2 group maintains (partially) its structure
- 2. Processes or products where the CO_2 group is broken down, to bring the C-atom in a newly established hydrocarbon structure

In the two text boxes (see Box 5-3 and Box 5-4), examples of both classes of CCU are described, to give an impression of possibilities and challenges associated to the use of CCU. Many different routes / products are being researched.

Currently, markets already exist for polymers and fine chemicals synthesised from CO_2 mainly in the first group where the structure is maintained. In the short term, overcoming technological hurdles for the commercial introduction of these high-value added CO_2 -derived polymers and fine chemicals could generate the momentum required to tackle the more difficult challenges related to the reduction of CO_2 to fuels or chemicals.

The long term paths of valorisation of CO₂ can have multiple benefits in terms of resource-efficiency:

- Avoiding emissions of CO₂
- Reducing the use of fossil carbon sources and closing the carbon cycle
- Contributing to electricity grid stability

Box 5-3 New structure: Utilisation of captured carbon for olefins

Cracker products (currently made in steam crackers) can alternatively be made by converting methanol to olefins using the MTO process. The methanol could be made on the basis of CCU. Traditionally, methanol is produced from natural gas, by steam reforming to synthesis gas. Alternatively, methanol can be produced directly from hydrogen and CO₂. To ensure reduction of CO₂ emissions, it is required to produce the hydrogen through electrolysis (using renewable electricity) rather than by gas-based routes. As such, cheap electricity is essential for the profitability of this route; this could also be periodically cheap electricity (peak shaving) provided that plants can be designed to run at different loads and that the overall economics of such plants are good enough. This route could also become more profitable in case new catalysts or processes would enable the use of low temperature heat (waste heat from other processes, cheap abundant geothermal heat).

An option at the boundary of CCU and bio-based chemistry is the use of sunlight. An example is future ethanol production from biomass from carbon dioxide (CO_2), salt water and sunlight using metabolically enhanced hybrid blue-green algae. The process takes place in photo-bioreactors and the feeding of algae in salt water is expected to require about two dry tonnes of CO_2 a day, for a pilot plant of approximately 0.3 kt of ethanol per year (Chemicals-technology.com, 2013).

Box 5-4 Maintain structure: Utilisation of captured carbon in Polymers

The fundamental advantage of incorporating CO_2 in products is that the CO_2 is built in the backbone of the polymer, so the existing structure of CO_2 remains, partly, in place. Consequently, the energy balance of the process can be less challenging because the CO_2 molecule does not need to be broken down. The challenge is to find useful chemicals in which the CO_2 structure contributes to its functionality. For example, polyols are widely used today, and could—in some applications—be replaced by polyols based on CCU. The potential of this route will, at the end, be determined by the properties of the CCU based products, and how these polymers compare in terms of functionality, costs and energy use. Many companies are researching the manufacture of CO_2 based polymers. This Roadmap assumes the implementation to still be very limited by 2020.

Some utilisation options assure a permanent removal, e.g. with the carbon ending up locked in minerals. For other options the utilisation is only temporary, and varies from days to tens of years, like in urea or polymers. When assessing the effect of utilisation of captured carbon, this should be taken into account and the overall GHG emission performance should be accounted for.

Many activities related to CO_2 utilisation as feedstock have already been initiated at national, regional and company level in and outside Europe. A scoping study on the utilisation of CO_2 as a renewable resource has been initiated jointly by Cefic and the European Association for Chemical and Molecular Sciences (EuCheMS) in 2012, in cooperation with a number of companies. The objective of this initiative is to create a European research and innovation Roadmap that would address the utilisation of CO_2 for the production of basic chemicals, fine chemicals, polymers and fuels considering different pathways including the photochemical conversion of CO_2^{30} by the end of 2013.

5.3 Improve energy efficiency of processes

Chapter 2 explained that, given the importance of energy costs for most of the European chemical industry, energy efficiency has always been high on the agenda of the sector.

Although a considerable improvement has been achieved, there are still opportunities for further increasing energy efficiency. On the one hand, energy efficiency can be improved by adaptation measures that apply to the current stock of installations. On the other hand, innovative techniques are available or under development that can be implemented when new installations are constructed.

This section first provides a catalogue of the energy efficiency improvement options available to the chemical industry (Section 5.3.1). Then it is described how energy efficiency potentials are calculated (Section 5.3.2). It should be stressed upfront that the potentials used cannot be applied as such to individual companies, as early adapters will have much lower saving potentials left, while others will have saving potentials well above average.

5.3.1 Options for energy efficiency improvement

Process intensification and other process improvements

Data concerning Process Intensification and other process improvements are based on VNCI (2012), McKinsey (2009), European Roadmap for Process Intensification (Creative Energy, 2007) and the SPIRE Roadmap (SPIRE, 2012), and on input provided in the context of the topic team Technology and Innovation.

Process intensification (PI) presents a set of often radically innovative principles in process and equipment design, which can bring significant benefits in terms of process and chain efficiency, capital and operating expenses, quality (due to a higher selectivity), wastes and process safety (lower volumes). It appears that most traditional chemical and physical technology processes have

³⁰ Production of bio fuels and chemicals from algae, using the sun as energy source. Not yet commercially ready for production of bulk chemicals or bio fuels, but with significant potential, as algae grow quickly and can be used as raw material for many industries (biofuels, chemicals, food). Significant innovations are still needed before bulk chemicals can be produced economically from algae (see also Box 5-3).

significant limitations in mass and heat transfer. For example, the limited mass and heat transfer in a traditional distillation column is caused by the relatively low Earth gravity. Increasing the driving force by a factor ten, for example by rotating equipment, could have the potential to reduce investment costs and energy use; however, turning this into reality is not straightforward.

Despite the fact that in the past spectacular improvements have been achieved for specific processes³¹, realising the full potential of PI cannot be taken for granted. Various barriers to PI implementation exist, such as the high cost to retrofit PI technologies in current plants, the lack of PI knowledge and unfamiliarity with the technologies, and the long development path. For energy-intensive plants operating in 2010, this means that the potential of process intensification is limited to replacing or adjusting existing energy intensive process steps. For new plants, the freedom to choose, and thereby the potential, is more substantial.

Within process intensification, two basic categories of technologies can be distinguished (SPIRE, 2012), as depicted in Figure 5-4:

- Process-intensifying equipment, such as novel reactors and furnaces, and intensive mixing, heat-transfer and mass-transfer devices;
- Process-intensifying methods, such as integration of reaction and separation, heat exchange, or phase transition, techniques using alternative energy sources, and new process-control methods.

Process intensification is driven by five generic principles (Creative Energy, 2007):

- 1. Maximise the effectiveness of intra- and intermolecular events
- 2. Give each molecule the same processing experience
- 3. Optimise the driving forces on every scale
- 4. Maximise the specific areas to which those driving forces apply.
- 5. Maximise the synergistic effects from events and partial processes.

To do so, new unit operations such as advanced heat exchangers, mixers, spinning disk reactors, HiGee separation technologies, or combinations like reactive distillations, heat exchange reactors and membrane reactors are developed.

³¹ Combining several steps in the formation of methyl acetate by a reactive distillation column led to 50% lower capital costs, and 85% lower energy use, lower conversion costs and plant footprint at Eastman Chemical Company (Agreda and Cwirko, 2007). Another example is Dow's High-Gravity Field reactor to produce hydrogen chloride, showing an increase in yield from 80% to 94–96%, a reduced equipment size by a factor 40 and 1/3 reduction in waste water and chlorinated by products (Stankiewicz, 2007).



Figure 5-4 Elements of process intensification (Creative Energy, 2007). The examples are in very different stages of development and have different and sometimes limited potential

Heat recovery and reuse

The effectiveness of heat use in the chemical industry can be further improved by optimising the use of the available heat. It is estimated that 20–50% of the energy used in industrial processes is lost in the form of hot exhaust gases, cooling water and heat losses from equipment and products (SPIRE, 2012). Recovery of energy from production processes has been done for decades. Nevertheless, further optimisation of heat integration, taking the increasing energy and CO₂ cost into account, offers further potential to reduce energy use. Solutions are often cross-sectorial. Their implementation depends primarily on the economic viability and perceived technical risks. For batch processes³², important factors also include a good timing between demand and supply of heat and security of heat supply, especially when crossing plant or company boundaries. Besides improving the economics of waste heat recovery techniques, cheap energy storage in combination with energy management systems are essential to tap the potential (SPIRE, 2012).

³² The majority of processes are continuous. When optimising heat integration for batch processes, heat should be available at the same time it can be used, or should be stored—which decreases the economical attractiveness.

Concrete measures include the application of total site pinch analysis, heat pumps, heat-absorption and cooling, Organic Rankine Cycles and finally heat exchange between companies in industrial conglomerates and (nearby) district heating. Several of these measures are already (partly) implemented on many sites, which reduces the room for further improvements.

On-site process integration (i.e. total site pinch analyses) optimises the heat exchange activities on a chemical site. Pinch analysis seeks the best match between the supply and demand of heat to the extent possible, including energy storage. At sites where no pinch analysis has been executed in the past, a technical fuel savings potential of 20-30%, with economic potential of 10-15%, can be typically realised (Linnhoff-March, 2000). Pinch analysis has been common practice in the chemical industry for decades. Revisiting earlier pinch analysis to account for changes in the process and for increasing energy and CO_2 costs can be beneficial. Saygin et al. (2011) estimate that fuel savings of 5% can be achieved. In larger sites more heat supply sources and processes with heat demand are available. Therefore a concentration of chemical activities in mega-clusters ("chemical parks") can increase the potential.

Upgrading the quality of the energy of waste heat includes low and high temperature heat pumps, heat pumps with high temperature lifts and thermally driven cold supply, where upgraded waste heat can either replace steam or electricity (SPIRE, 2012). In general this covers all novel processes to transfer sensible heat from a medium where this heat can currently not be utilised into a medium which makes this energy available at the maximum available temperature. Developments are targeted at e.g. improving the characteristics of heat transfer (higher temperatures, applicable in dusty and corrosive environments), storage of energy at different temperatures and gas separation at high temperatures (SPIRE, 2012). Cascading of heat to make optimum use of the quality is also an option to consider. In the chemical industry, high temperature heat e.g. from furnaces is already many times recovered as ultra-high pressure steam, which in turn is used to drive compressors, as these need a lot of energy which is provided most efficiently by steam. The remaining steam is used at the lower pressure levels according to the pinch principle.

Heat pumps can increase the temperature of waste heat to levels at which it can be used as process heat (Wolf et al., 2012). The maximum temperature lift that can be achieved and the maximum temperature limit the potential of heat pumps, as some of the processes require heat at temperatures that are too high and remaining demand for low temperature heat is already partly delivered by heat integration. Innovative systems such as thermo-chemical and thermo-acoustic heat pumps are under development to achieve higher temperature lifts (Bach, 2007) and thus higher potential. Organic Rankine Cycles (ORCs) can convert waste heat into power. In an ORC, an organic working fluid is applied, with a lower boiling point than water. Investment costs of ORCs are currently still high compared to other power generation technologies (EPA, 2012).

Heat-absorption cooling can convert waste heat into cooling. Many processes, for example polymer and rubber processes, need a significant cooling.

Further development is needed for efficient and cost-effective alternatives for waste to electricity techniques (SPIRE, 2012).

Waste heat of chemical sites can be used to meet others' heat demand, for example the use of waste of heat for district heating, where the economic viability depends largely on costs for the distribution network and the demand pattern and heat integration between a fertiliser plant and a horticulture complex. There are many more possibilities for heat exchange between the chemical industry and its vicinity, and this possibility can also be taken into account when developing areas around chemical installations (for example: look for a new neighbour with a heat demand). Important barriers are the risk in the security of supply, (in some cases) the economics, the lock-in situation that heat exchange can cause³³ and the distribution of (investment) costs and risks.

Efficient use of power

Motor systems are by far the most important user of electricity in industry. They are responsible for about two-thirds of the power used in the chemical industry, if electricity used for chemical conversions is excluded (e.g. power used for the production of chlorine). Motors are used to drive all kinds of equipment essential to the chemical industry, like pumps and fans and centrifugal compressors. The efficiency of a motor system depends not only on the efficiency of the motor itself but also on factors like motor control, proper sizing, transmission, maintenance and the efficiency of the motor-driven equipment.

There are three main routes to achieve savings in motor systems:

- 1. Use of properly sized and energy efficient motors.
- 2. Use of variable-speed drives (VSDs), where appropriate, to match motor speed and torque to the system mechanical load requirements.
- Optimisation of the complete system, including correctly sized motors, avoidance of (useless) backflows, pipes and ducts, efficient gears and transmissions, and efficient end-use equipment (fans, pumps, compressors, traction, and industrial handling and processing systems) to deliver the required energy service with minimal energy losses.

The savings on electricity use of motor systems are in the range of 17–30% (IEA, 2009a; Keulenaer et al., 2004; IEA, 2011b; IEA, 2012c; Ecofys, 2009). Most of these measures are profitable.

Lighting can account for 7% of the total electricity consumption of chemical plants (although in many cases, the share of lighting is much lower) with an average saving potential of 15–25% (IEA, 2009a).

³³ After investing in the infrastructure for heat exchange, improving a process in such a manner that waste heat would no longer be available.

On-site energy generation and distribution

A reduction of 3% of the fuel demand could typically be achieved by measures to make *boilers more efficient.* Typical measures are improved process control, offline or online supply-demand optimisation by MILP (mixed integer linear programming), reduced flue gas quantity, flue gas heat recovery, and regular maintenance. Fuel savings in *steam distribution systems* of 5% could be realised by, amongst others, improved and better maintained steam traps, leakage repair and condensate return (Neelis et al., 2008; IEA, 2009b). *Better insulation* can lead to an additional saving of 1.5% (Ecofys, 2012). Also for these measures, it should be stressed that the potential differs widely between different subsectors and individual sites. Many companies have good energy management systems in place and already keep good track of the on-site energy generation and distribution systems, limiting the potential to further improve.

New energy and resource management concepts

In the longer run, significant improvement of the energy consumption and CO_2 emissions will be achieved thanks to the optimisation of interdependencies both among stakeholders inside industrial parks and outside the park (SPIRE, 2012). Inside the industrial park, new energy and resource management systems require integrating demand side management and decentralised energy and resources. These systems must offer standardised approaches that optimise cost savings in energy and resources supply and demand on the basis of new and innovative analysis tools.

Outside the park, interactions for example between companies, neighbouring municipalities and infrastructure administrations can lead to several positive effects for all stakeholders. Examples are increased economic value, higher level of attractiveness to investors, new clients and more jobs created. New business models and service concepts are required to address the barriers that prevent these solutions. For instance new more intensified, lower capital, but more flexible production units could allow greater distribution of process manufacturing closer to end-users and customers. As transport energy costs rise, this will generate economic and environmental benefits.

5.3.2 Generic improvement approach

For all chemicals, except for ammonia, cracker products and chlorine (to be discussed in Section 5.6), an approach based on the development of the energy intensity over time is followed. The energy intensity of a sector is the energy use in GJ per sales value. The following two determining parameters are taken into account:

- 1. Developments in the process final energy use in GJ / tonne, i.e. technical efficiency improvements;
- Developments in the product mix in € / tonne (i.e. structural effect towards the higher value added products and development of new ones).

A distinction is made between stock operating in 2010 and new stock of chemical plants. For *stock operating in 2010* the technical efficiency improvement potentials have been set based on the information about the energy efficiency improvement potential of the options described above, validated by information from historical trends, and improvement potentials for the individual products studied in this Roadmap. For example, for five important Polymers (polypropylene, high density polyethylene, low density polyethylene and linear low density polyethylene and polystyrene), a time series from 1993-2011 was available on the development of energy efficiency over time, pointing at improvement rates of approximately 1% per year over the last 20 years (PTAI, 2013), which is in the same order of magnitude as the technical efficiency improvements derived from the options described above. Over time, the improvement rate has slightly decreased and no new breakthrough technologies with lower emission per tonne of product are in the pipeline, limiting future potentials.

The developments in the product mix (the structural effects towards higher value added products) have been estimated as expert judgements by the topic team Technology and Innovation. Improvement in the energy intensity due to changes in the product mix are based on the expectation that there will be a gradual shift towards more specialty and innovative products with higher value (e.g. the innovative examples given in Chapter 8). This effect is expected to be limited for basic chemicals, more relevant for the Speciality and Consumer Chemicals and more in between for Polymers.

The resulting improvement potentials are shown in Figure 5-5 to Figure 5-8 per subsector and separately for the improvement potentials related to the use of electricity and those related to the use of fuels and heat.³⁴ In Section 7.3.2, it explained how the potential as given in these figures are applied to arrive at scenario-dependant energy efficiency improvement potentials.

³⁴ The potentials can thus not be added, but are applicable to different parts of the final energy use: the electricity use and the use of fuels / heat.


Figure 5-5 Generic electricity efficiency improvement for *stock operating in 2010,* 2010-2030 (numbers exclude the products studied individually—cracker products, ammonia, chlorine)



Figure 5-6 Generic electricity efficiency improvement for *stock operating in 2010,* 2010-2050 (numbers exclude the products studied individually—cracker products, ammonia, chlorine)



Figure 5-7 Generic fuels / heat efficiency improvement for *stock operating in 2010,* 2010-2030 (numbers exclude the products studied individually—cracker products, ammonia, chlorine)



Figure 5-8 Generic fuels / heat efficiency improvement for *stock operating in 2010,* 2010-2050 (numbers exclude the products studied individually—cracker products, ammonia, chlorine)

The potentials reflect the different positions of the different technologies in the innovation cycle (Figure 5-9 visualises the idea). Basic technologies which have been improved over the years show lower improvements than the multitude of products at the end of the value chain, many of which

have a much shorter history. Industrial ammonia production looks back to 100 years of history, while Polymers began their success story about 70 years ago. Some Consumer Chemicals have only entered the market in recent years.



Figure 5-9 Improvement potential depends on position in the innovation cycle

Figure 5-9 also makes clear that constant annual improvements in energy efficiency can only be expected for a certain time but come to an end when the process reaches a fully optimised state. Improvements beyond the innovation curve of a process can only be reached by jumps toward another curve. This is more likely for complex products which can be built up by various chemical synthesis routes than for very basic chemicals with simple structures. This effect partly contributes to the high improvement potentials shown for Consumer and Specialty Chemicals further down the value chain. Of course, the improvement potential for these two subsectors depends strongly on the product. The process illustrated in Figure 5-9 cannot be applied to all products in these subsectors.

It should be noted that the calculation with constant annual improvement rates in the following chapter is a simplified, mathematical approach. In reality, periods of limited improvement rates alternate with game-changing breakthroughs leading to much higher yearly improvement rates.

For *new stock,* current best practice technologies are compared to the current average and take into account the development of the best practice technologies. Current best practice technologies have energy efficiencies that are 10–50% better than the average (Saygin, 2012). This is confirmed by analysis of the individual products ammonia, cracker products and chlorine as studied in this Roadmap. As a starting point for this Roadmap, it is assumed that new plants currently built are typically 30% more energy efficient compared to the current average. Improvement factors for new

stock are applied in such a way that the gap between average and new stock is reduced to a 15% difference in 2050.

5.4 Heat source changes, renewables and CHP

A *shift to low carbon fuels* to produce heat does not necessarily improve the efficiency of heat generation but will result in lower GHG emissions. This option is taken into account by defining, for each scenario, a future mix of fuels to be applied, based on the development of the prices for the various fuels. It should be noted that, for biomass, upstream GHG emissions related to growing the biomass can be substantial, but that these GHG emissions are not taken into account in this Roadmap (Box 5-5).

Geothermal heat can provide heat to some chemical processes. The use of geothermal heat is limited by geographical availability and to processes that need a temperature up to approximately 250 °C. This limits its applicability to only that part of the heat demand. It should also be noted that a substantial part of this low temperature heat is available to the chemical industry as cascaded waste heat available from high temperature processes, thereby further limiting the application of lowquality geothermal heat, because priority will always be given to the readily available heat sources from cascading. The costs for geothermal heat are expected to come down from 7.5 \in / GJ in 2010 to $5.4 \in$ / GJ in 2050³⁵. Risks associated with geothermal projects are relatively high, making it difficult to find financing for the upfront investments. These low prices show that geothermal heat could become, in some cases, an attractive source of low temperature heat in the future. However, the potential is limited due to the limitations described above.

Combined generation of heat and power (CHP) can save fuel compared to generating heat and power separately if the heat can be used. CHP is already widely applied, supported by several national programmes. Currently the profitability is under pressure due to the current natural gas and electricity prices as a recent report for the Netherlands shows (COGEN Europe, 2013). At a certain time, fossil fuelled CHP will have higher carbon intensity per unit of power compared to centralised power production using large shares of renewables. This implies that to further decarbonise, CHP would be used in biomass applications and / or in combination with carbon capture and storage. Projections from the EU Energy Roadmap (European Commission, 2011b) are used in this Roadmap when it comes to future application of CHP by using a CHP included electricity emission factor derived from the EU Energy Roadmap (see Section 7.3.3 for more details).

³⁵ Ecofys analysis

Box 5-5 Emission factor of biomass

In line with the scope 1 and 2 demarcation chosen for this Roadmap, a zero emission factor for biomass resources used as fuel or feedstock by the European chemical industry is applied, excluding emissions related to the upstream cultivation and processing of biomass. However, life cycle GHG emissions related to the production of biomass can be substantial and are the subject of intense debate in relation to the overall sustainability assessment of biomass use. Two upstream GHG emission sources related to biomass can be distinguished:

- Direct GHG emissions related to the biomass production activities such as those related to farming activities, fertilizer production, transport and distribution and biomass processing, including any direct emissions caused by a change in land use from high carbon stock land (e.g. forest) to lower carbon stock land (e.g. agricultural land).
- GHG emissions related to indirect land use changes. Competition for land use might result in biomass cultivation activities causing land-use changes elsewhere, e.g. forest to agricultural land conversion induced if existing cropland is used for bioenergy feedstock production.

The order of magnitude of these two sources depends heavily on the type of biomass used and the regions and type of land where the biomass is cultivated. The renewable energy directive (European Commission, 2009) gives ranges of 4–57 g CO₂e per MJ of biofuel for the typical direct life cycle GHG impact of biofuels in transport, and 1 to 30 g CO₂e per MJ biomass for solid biomass used for power generation (European Commission, 2010). Typically, these emission factors are lowest for solid wood based biomass, for wastes and residues and for 2^{nd} generation ligno-cellulosic based biofuels, as compared to 1^{st} generation biofuels based on food crops. Indirect land-use change emission factors, by definition, have to be modelled and are subject to intense debate. The European Commission has proposed indirect land-use change factors ranging from 12 g CO₂e per MJ biofuel for cereal crops to 55 g CO₂e per MJ biofuel for oil crops (European Commission, 2012c; IFPRI, 2011). Work is still on-going to estimate indirect emissions from 2^{nd} generation biofuels and solid biomass. The ranges above indicate that the life cycle GHG emissions from biofuel use in transport could be a substantial part of the direct emission factor from fossil fuels.

In view of the above, it is important to take the full life cycle GHG emissions of all forms of biomass into account in assessing the sustainability of biomass and to further standardise the sustainability criteria for biomass use. In Germany, an initiative on this (INRO) has already been started by the Federal Ministry for Food, Agriculture and Consumer Protection, aiming to develop sustainability criteria for the sustainable supply of raw material for bio-material use. In this Roadmap, solar heat is not specifically assessed, although relevant cost decreases are expected³⁶. Solar heat application is limited to the southern European countries (i.e. it is expected to be only feasible from a certain latitude, approximately from northern Spain, central Italy and northern Greece downwards). As only a small part of European chemical industry is located at those latitudes—about 10% of total heat demand—its application is limited to a few percent, due to both geographical as well as temperature level constraints. This was also confirmed in the regional workshops organised in the context of this Roadmap (Section 1.4). Solar heat is therefore not further assessed in this Roadmap.

5.5 End-of-pipe emission abatement

5.5.1 Carbon capture and storage (CCS)

This analysis is based on IEA (2012c), IEA & UNIDO (2011), Blomen et al. (2009), ZEP (2011), Broek (2010), Kuramochi (2011), Rubin et al. (2007), Broek et al. (2009), Damen (2007), Berghout et al. (forthcoming) and on Ecofys expert opinion.

Capture of CO_2 is not a new technology. CO_2 has been captured for nearly 100 years for industrial purposes or to increase oil production. However, capturing CO_2 with the intention to combat climate change is relatively new and, up to now, only occasionally applied. Its development could be symbiotic with the development of CCU (refer to Section 5.2.3).

There are three different types of CO₂ capture systems:

- Post-combustion (capture from flue gases);
- Pre-combustion (capture by conversion of fuels); and
- Oxy-fuel (capture by using by combustion with pure oxygen instead of air).

In some industrial processes, e.g. ammonia production, a highly concentrated CO_2 stream is produced. In that case, only purification and dehydration is required. Technical improvements in the capturing of CO_2 will reduce investment, operation and energy-related costs. In some cases, captured CO_2 can be utilised on-site. This is, for instance, already common practice in the production of urea by using CO_2 from a nearby ammonia plant. In most cases, the captured CO_2 needs to be transported to the place where it is either stored or used. Large amounts of CO_2 are most efficiently transported either by pipelines or by ship. Before transportation, the CO_2 needs to be purified and compressed / liquefied. The costs for transportation of CO_2 depend on transport volumes, transport distance and possibilities to use existing infrastructure.

³⁶ Ecofys analysis

 CO_2 can be injected and stored in onshore or offshore geological formations. Feasible storage locations are (depleted) oil fields, depleted gas fields, saline formations, not commercially extractable coal seams, and saline-filled basalt formations. Impermeable cap rock and geochemical trapping mechanisms prevent the CO_2 from escaping to the surface. Saline aquifers offer a large potential storage volume, but the disadvantage is that relatively little is known about them, especially compared to hydrocarbon fields. Storage costs vary widely depending on volume, location and the characteristics of the reservoir (e.g. depth, type, permeability).

The attractiveness of CCS depends on the CO_2 emissions volume, as all steps in CCS will be cheaper per tonne of captured CO_2 with increasing volumes. In this Roadmap, ammonia production and steam crackers are assessed separately and other chemical production more in general. For CCS, this means that per subsector the average plant size and the economic viability of CCS is assessed.

Investments in CCS consist of capture and compression, transport and storage. In general, the variability of these investment costs is high. CCS is currently still in its first generation technology which is mainly in the demo phase. With the assumption that CCS takes off and worldwide installations will be built, the costs will go down—learning by research and by doing. This learning will only take place if CCS is picked up by many sectors, which is the working assumption for the scenario where a significant share of CCS uptake is foreseen by the chemical industry.

Oxyfuel using oxygen from an air separation plant (ASU) is assumed to replace post-combustion towards 2030. From 2030 onwards new technologies such as the use of oxygen conducting membranes—instead of ASU—in the oxyfuel technology may be used. This may lead to large cost reductions, both in energy and investment costs; the latter has not been taken into account in the scenarios.

This Roadmap looks into the costs for CCS for three sources of CO₂:

- Ammonia (pure AND combustion sources, typical plant size 1.2 Mt CO₂ / year, respectively 0.8 Mt CO₂ / year)
- Cracker products (combustion sources, typical plant size around 0.7 Mt CO_2 / year, significantly more for new crackers, up to 1.5 Mt CO_2 / year due to the higher capacity of these crackers)
- Combustion general (typical plant size 0.05-0.2 Mt CO₂ / year)

Figure 5-10 shows the total investment costs for capturing, transporting and storing CO_2 for the first two sources, whereas Figure 5-11 gives annualised figures for combustion sources of various sizes. A detailed overview of the cost assumptions on CSS is given in Annex 1.



Figure 5-10 Development of investment costs for CCS applied to ammonia production (top), new steam crackers (middle) and existing steam crackers (bottom). The black bars depict uncertainty ranges



Figure 5-11 Relation between the capturing costs and the scale of CO₂ emissions from combustion sources. The blue surface indicates the *annualised* investment costs (for *total* investment costs, see Figure 5-10)³⁷

For the (generic) subsectors, the potential for CCS has been estimated by combining two sources; first by using ETS emissions data from the Community Independent Transaction Log (CITL) database and linking the data with NACE codes to the subsectors. Secondly, a typical distribution of (steam) boilers and CHP installations for chemical industry was related to boiler and CHP size of subsectors. This leads to a differentiation of economic potential between subsectors, as depicted in Figure 5-11. Differences in energy costs resulting from the different scales are neglected.

Costs for CCS on flue gases from combustion are lowest for the production of cracker products due to the scale of these installations and increase for smaller emission sources. There are locations with limited CO_2 storage locations (e.g. Finland, Belgium), but considering the typical location of large chemical industry, as well as the possibilities for transporting CO_2 (e.g. Antwerp \rightarrow Rotterdam), this would not significantly limit the application of CCS for the EU chemical industry.

 $^{^{\}rm 37}$ Using electricity prices from the Differentiated Global Action scenario.

Apart from being stored (CCS), captured CO_2 can also be used (CCU). Its use as feedstock in the chemical industry has been discussed in Section 5.3.2. Other uses are possible as well:

- Enhance hydrocarbon production (enhanced oil recovery, enhanced coal bed methane)
- In greenhouses (to enhance growth of the plants)
- In the food / soft drinks industry
- To produce fuels
- As raw material for inorganic materials

The duration of storage of the CO_2 and the net reduction of CO_2 emissions varies over these uses.

Combining the use of biomass with CCS or CCU has not been assessed in this Roadmap, but could be an interesting future option to reduce the chemical industry's GHG impact even further.

5.5.2 Other GHG emissions: the case of nitric acid production

Data on GHG abatement measures for stock operating in 2010 and new stock have been identified, characterised and validated by the topic team Technology and Innovation.

Nitric acid is synthesised by the oxidation of ammonia in the presence of a catalyst. Ammonia and nitric acid are often produced at the same site.

The production chain of nitric acid involves the synthesis of nitric oxide (from the oxidation of ammonia), which is subsequently oxidised to nitrogen dioxide. The latter is absorbed in water to form nitric acid and nitric oxide, which is cycled back for re-oxidation. At high pressures and low temperatures, this intermediate nitric oxide (NO) readily decomposes to nitrogen dioxide (NO₂) and nitrous oxide (N₂O), which is a strong GHG. This section focuses on abatement of N₂O.

In 2007 / 2008, the average emissions were 4.7 kg N₂O per tonne of nitric acid (value determined within the context of the topic team Technology and Innovation). Since then, more plants have installed abatement technologies and the average emission rate has been reduced. Official EU data (EEA, 2013; UNFCCC 2012) for 2010 give an average emission figure below 1.5 kg N₂O per tonne of nitric acid. However, these figures do not cover all nitric acid plants in the EU³⁸. A value of 2.9 kg N₂O per tonne of nitric acid produced is deemed to be representative for the average European plant in 2010 (determined by the topic team Technology and Innovation).

For the abatement of nitrous oxide, two types of measures are possible:

³⁸ Coverage of only the plants that have installed technology under JI or opt-in.

- 1. Measures that remove N_2O from the process gas stream between the outlet of the ammonia oxidation and the inlet of the absorption tower ('process in-built'),
- 2. Measures that reduce N_2O after the absorption process ('end-of-pipe').

Nitric acid plants either take the first or the second measure; technically it does not make sense to implement both. In Figure 5-12 the *combined effect* of the two measures is indicated with respect to the 2010 baseline N_2O emissions.



Figure 5-12 Technical potential in 2050 for N₂O abatement in nitric acid production. Economic feasibility is not taken into account

By 2020 all plants are expected to have installed abatement technology with an average emission level of 0.7 kg N₂O per tonne of nitric acid, decreasing further to an average of 0.4 kg in 2030 and 0.3 kg in 2050. Investment costs for N₂O abatement, expressed in their equivalent CO₂ abatement costs, range from 7 to 190 \in / t CO₂e, depending on the type of measure, the current layout of the plant and temperatures of the tail gas.

New nitric acid plants built after 2020 can achieve capture rates of 95% for inbuilt technology and 99% for end-of-pipe technology, which corresponds to emission levels of approximately 0.4-0.1 kg respectively of N₂O per tonne of nitric acid produced. An average capture rate of 96% is taken into account for new stock.

In this Roadmap, it is assumed that N_2O emissions from the production of other chemicals (adipic acid, glyoxal and glyoxylic acid and caprolactam) follow the same reduction pathway as the N_2O emissions from nitric acid production.

5.6 Product group-specific abatement options

In the subsequent sections, measures that are specific for the product are described. The products addressed are ammonia, cracker products and chlorine. Different options for improving energy efficiency, GHG abatement and new types of installations are discussed.

5.6.1 Ammonia

For currently existing ammonia plants, data on measures were found in Rafiqul et al. (2005). The potential from this source was confirmed by the topic team Technology and Innovation.

For new stock, data on characteristics are dispersed and originate from different sources: detailed assessment biomass gasification by industry, alternative future technologies from U.S. DOE (2013) and Ganley et al. (2007), and CCS measures by Ecofys experts. Validation was done by the topic team Technology and Innovation.

Ammonia is synthesised by a reaction of nitrogen and hydrogen over a catalyst. While nitrogen can be obtained from air, hydrogen has to be produced from other feedstock. The most widely used process to produce hydrogen is steam reforming of natural gas. To a far lesser extent, partial oxidation of heavy fuel oil or vacuum residue is used. In the European Union, no new ammonia plants have been taken into operation in the past two decades.

The sequence of operations to produce ammonia from natural gas starts with feedstock preparation (desulphurisation), followed by primary and secondary reforming and the water gas shift reaction. Oxygen compounds are removed in two steps, CO_2 -removal and methanisation. The resulting gas contains hydrogen and nitrogen in the ratio 3:1 and is converted to ammonia in a synthesis loop under high pressure and low temperatures. Ammonia plants are sometimes co-sited with a urea plant as the CO_2 produced in the ammonia process is a feedstock for urea production.

The energy demand of the current stock of ammonia plants is 35 GJ / t NH₃. Figure 5-13 shows how this specific energy consumption can be reduced to about 32 GJ / t NH₃ by applying measures to plants operating in 2010. The thermodynamic minimum, if one assumes full recovery of all heat possible, is equal to the heating value of ammonia, which is 18.6 GJ / t NH₃ (this is considered the feed for the current ammonia process). However, some energy is required to enable the reforming reaction, so the theoretical minimum energy consumption is currently around 23 GJ / t NH₃ (Fertilizers Europe, 2012).

In the <u>reforming section</u>, energy efficiency improvement can be achieved by a combination of larger and moderate improvements. Examples of options are the addition of a pre-reformer, lowering the steam to carbon ratio, avoidance of heat loss by insulation and an increase in operating pressure. Since most ammonia plants have already improved the energy performance of their reformers in the past decades, the total remaining contribution to bringing down the energy demand is only limited. Improvements in other operations of the ammonia plant are <u>improved CO_2 -removal</u> and <u>low-pressure</u> <u>ammonia synthesis</u> by improved catalysts, which can still be applied to about 90% of the ammonia plants. Further improvements can be achieved by <u>advanced integration</u> of the heat exchanger network in the plant, <u>improved process control</u> and <u>improved motor systems</u>.



Figure 5-13 Technical potential for energy efficiency improvements in existing ammonia plants in 2050. Figure includes feedstock use. Economic feasibility is not taken into account

An analysis of the actual improvements in the energy efficiency of ammonia plants in Europe shows that over the last decade very few improvements have been made. Between 2004 and 2011, even a slight decline of -0.17% per year was observed for a group of 26 European ammonia plants. The causes for this decline are reported to be unclear. In this respect, it should be noted that the European ammonia plants are, as a whole, the most efficient ones globally. Future energy efficiency improvements depend on the technical and economic ability of plant operators to do energy reduction projects requiring additional investments (PSI, 2012). Energy efficiency improvements in existing ammonia manufacturing facilities will thus not take place automatically (see also Chapter 7) but depend strongly on planning security, which in turn depends on the policy framework.

Apart from improving energy efficiency, the GHG emissions of ammonia production can be decreased by <u>carbon capture techniques</u>. Carbon emission from ammonia production stem from two sources: flue gases from combustion processes and process emissions from the reforming reaction. The last source of CO_2 is sometimes used as feedstock in the urea production or other downstream utilisation. However, as CO_2 is not captured long term, it is e.g. released upon use of urea; this is not a permanent solution from a lifecycle perspective taking account of the fertiliser application. Carbon capture and storage is further discussed in Section 5.5.1.

<u>New ammonia plants</u> can already achieve an energy³⁹ demand of 28 GJ / t NH₃ (see Figure 5-14). These new processes obtain their higher energy efficiency by an optimised steam reforming section (part of the reforming duty is shifted from the primary to the secondary reformer), a low pressure synthesis loop and a better process integration. Experts within the topic team Technology and Innovation indicated that the energy demand of Greenfield ammonia plants can be expected to be as

³⁹ Fuel, heat, electricity and feedstock are included here.

low as 28 GJ / t NH_3 by 2020, 27 GJ / t NH_3 by 2030 and 26 GJ / t NH_3 by 2050, when the process is highly integrated with other industrial processes or heat recovery systems.

Another option to abate the carbon emission of ammonia production is to <u>change the process of</u> <u>hydrogen generation</u>. Hydrogen can be produced out of other feedstock and biomass is a particularly promising option. Biomass can be converted in a gasifier to produce hydrogen. Availability of the feedstock is a major limiting factor for the application of this technology. More about using biomass as feedstock can be found in Section 5.2.1.

Hydrogen can also be obtained by <u>electrolysis of water</u>. The carbon abatement potential depends strongly on the electricity mix. If electricity can be generated free of GHG emissions, e.g. by renewable energy sources, 100% of the CO_2 emissions of ammonia production can be avoided. Using the current electricity mix, water electrolysis does not result in lowering the carbon emissions of ammonia production. However, for 2030 or later, due to the greening of the power sector, this might become the case. The U.S. Department of Energy investigated several next-generation technologies to produce hydrogen, amongst others by using a high temperature nuclear reaction. A new development is the Solid State Ammonia Synthesis (SSAS) process, which uses only electricity. The target use is 7–8 MWh / t NH₃. Both technologies are not yet proven, although the first SSAS plant is announced to be built on a commercial scale (Ganley et al., 2007).

In Figure 5-14, alternative ammonia production technologies are compared to the baseline technology, being steam methane reforming.



Figure 5-14 Energy and feedstock uses of new ammonia plants. The feedstock energy represents the heating value of ammonia. Data reflect final energy use in 2050

5.6.2 Cracker products

The data on routes existing in 2010 for olefin production are based on Ren (2009), IEA (2009a) and Neelis et al. (2008). Further input and validation of the assumptions and data was done by the topic team Technology and Innovation. For characteristics of new stock for cracker products, a combination of academic and industry data has been used. These data have been validated by the topic team Technology and Innovation.

Cracker products are produced in steam crackers. In this Roadmap, the term "cracker products" used in the context of steam crackers is used for ethylene, propylene, butadiene, acetylene, benzene and hydrogen. These cracker products are part of the subsector Petrochemicals and are important intermediates and feedstock for the production of many other chemicals such as the Polymers polyethylene and polypropylene. Naphtha, a crude oil fraction, is by far the most important feed in Europe. In other continents, steam crackers also use ethane, propane and butane as a feed, depending on the pricing of the different feeds and the desired product mix. A typical naphtha-based steam cracker consists of three parts:

- Feedstock (naphtha)—diluted with steam—is heated in furnaces to 750 °C-900 °C in the radiation section, where naphtha is cracked into products of lower chain length. After leaving the furnaces, the hot gas mixture is rapidly cooled down. To use the heat efficiently, steam is recovered at various temperatures and pressures.
- The cracked gas is cooled to around 150 °C and most benzene, toluene, xylene and fuel oil are separated off. In the next step, water from dilution steam is separated off and recycled to the furnaces. The remainder of the cracked gas—containing mainly the other cracker products—is compressed.
- Finally, the different fractions of the remainder of the cracked gas are separated and purified for each specific product. The obtained methane is sent to the furnace section where it is used as fuel.

The average energy demand of currently operating naphtha crackers is 18 GJ / tonne cracker products. State of the art naphtha crackers use 11 GJ / tonne cracker products (information obtained within the topic team Technology and Innovation)⁴⁰. In recent years, at best small energy efficiency improvements have been made in the European steam crackers according to the topic team Technology and Innovation as described below.

A general factor limiting the total potential from many of the measures described below is that a steam cracker produces and consumes steam (at several temperature / pressure levels). When

⁴⁰ In addition to the fuel use, feedstock is used. The amount of feedstock for cracker products is defined in this Roadmap as the caloric value of the cracker products corrected for the endothermicity leading to a feed energy of 42 GJ / tonne cracker products. The endothermicity is the heat of reaction needed to produce cracker products from feed and is included as part of the energy use. The actual intake of naphtha is higher, but some products (not the "cracker products") are used outside the chemical industry.

optimising the energy consumption of a steam cracker, the total steam balance of the cracker—and its vicinity—should always be taken into account, as there is no point in saving steam consumption and ending up with an excess of steam which would then be vented.

Improving plants operating in 2010

Improvements in the energy efficiency of crackers operating in 2010 can be achieved in:

The furnace section:

- Improving the coils (leading to reduced coking and thereby improving the heat transfer, possibly also leading to increased selectivity);
- Optimising the heat balance of the furnace, maximising heat use at the temperature it is available, and minimising the heat losses through the stack⁴¹;
- Burning part of the fuel before the furnace in an integrated gas turbine, to produce additional electricity or drive compressors; this has only a very limited potential as a retrofit option, due to costs, reliability and burner configuration, and the produced / excess high pressure steam needs to have an efficient use.
- Optimising production of steam in the Transfer Line Exchangers.

In the <u>fractionation and compression section</u>, most gains in energy efficiency can be achieved by reducing the energy use of the compressor, by changing internals, improving inter-stage cooling or reducing fouling. The energy source (condensing or back pressure steam, electricity) has an impact on the efficiency as well. The energy consumption of compressors depends on the (amount of) gases it needs to compress and therefore depends on the specific layout of a plant – which depends on other factors as well. Once it has been built, changing this layout is not straightforward. In future, early membrane separation of alkanes (ethane and propane sent back to the furnaces) might become an interesting option—also eliminating the currently energy intensive ethane-ethylene and propane-propylene separations.

In the <u>recovery and separation section</u>, improving distillation columns (internals, new concepts like divided wall or heat integrated distillation) or replacing them by membrane separation (which needs further innovation) offers possibilities to improve the energy efficiency.

In general, advanced process control—usually implemented to optimise production—has as a side effect on energy efficiency improvement. Minor savings could be achieved from improved insulation and energy efficient lighting.

⁴¹ Condensation of the water in the flue gas—and associated corrosion problems—determines the minimum required heat loss.

Significant savings could also come from optimising the heat integration over the full plant, but also in relation with its vicinity. This could imply the use of (innovative) heat pumps, providing steam to other plants on the location, attracting new heat consuming business to the close vicinity of the crackers, or supplying heat to existing neighbours. The overarching goal is to optimise steam generation and use. The potential here depends very strongly on the current integration of sites and is strongly site-specific.

Based on the above, the energy efficiency of stock operating in 2010 is expected to improve by 14-21% (2030) and by 23–34% (2050) compared to 2010. These improvements will only be realised when innovative technologies are further developed and become proven technology. The economic attractiveness of retrofitting is only known for part of these innovative technologies.

Capturing of CO_2 from the flue gases via carbon capture and storage is discussed in Section 5.5.1.

New plants for the production of cracker products

The best <u>crackers</u> based on state-of-the-art steam cracking of naphtha can currently achieve an energy demand of 11–14 GJ / tonne cracker products (Ren, 2009). The higher energy efficiency compared to the average steam crackers is in general due to improved heat integration and heat transfer, high efficiency compressors, a different severity⁴², lower coking and maximisation of olefin yields. Based on input from the topic team Technology and Innovation, the lower limit of this number is used as the baseline technology: 11 GJ / tonne cracker products. Over time, for 2020: 11 GJ / tonne cracker products, for 2020–2030: 10 GJ / tonne cracker products and for 2030–2050: 9 GJ / tonne cracker products.

<u>Catalytic</u> olefin technologies can reduce activation energy use in the pyrolysis section of naphtha steam cracking processes, thereby operating at moderate temperature and pressure in comparison with steam cracking. The energy consumption by catalytic cracking of naphtha is estimated to be 10-11 GJ / tonne cracker products, approximately 10–20% less than state-of-the-art steam cracking (Ren, 2009). It is assumed that the energy consumption of the future new steam cracker is approximately comparable with catalytic cracking (which uses naphtha as feedstock as well). Therefore, no further distinction was made between catalytic cracking and steam cracking.

Other options to lower carbon emissions of cracker products production are the use of alternative processes to produce specific types of olefins, e.g. ethylene or propylene. Most of these processes use other feedstock, particularly biomass.

⁴² The severity is related to the cracking temperature, which can be used to control the types of cracker products and other products that are produced depending on product prices etc.

<u>Biomass from 1st generation</u> sources (e.g. sugar cane) can be directly fermented under anaerobic conditions to ethanol, which can consequently be dehydrated to ethylene. Here, the fermentation of the sugar cane is outside the scope of the Roadmap, because ethanol as feedstock is purchased as a commodity on the world market. Alternatively, lignocellulosic <u>biomass (2nd generation)</u> can be hydrolysed to glucose and consequently fermented to ethanol. In that case, the woody biomass is purchased, so the whole chain from biomass hydrolysis to ethanol dehydration is under consideration. The woody biomass can also be converted into methanol via gasification and subsequent methanol synthesis. This produced methanol can be used to produce olefins with the so-called "Methanol-to-Olefins" (MTO) technology. The amounts of biomass needed for these routes— expressed in GJ's—can be significantly higher than the amounts of fossil fuel and feedstock for the fossil based routes, and amounts of by-products (such as cogenerated electricity) vary over the biobased routes. Availability of the biomass feedstock is a major limiting factor for application of these technologies. More about using biomass as feedstock can be found in Section 5.2.1.

<u>Natural gas</u> (containing primarily methane) can also be converted into methanol via steam reforming to synthesis gas. Alternatively, <u>plastics waste</u> can be used to produce synthesis gas and methanol. This methanol can subsequently be converted to olefins, similar to the biomass to methanol route described above. The plastic waste can also be converted to 'waste naphtha', which would involve one step less. However, this is not considered here as historical economical evaluations of that process were not favourable.

In Figure 5-15, alternative cracker products production technologies are compared to the baseline technology, being naphtha steam cracking.



Figure 5-15 Energy and feedstock use of new plants for the production of ethylene and other cracker products. Feedstock use defined as calorific value of the products corrected for endothermicity. Data reflect final energy use in 2050⁴³

⁴³ The energy consumption of the "plastic waste to methanol to olefins" route is not included in Figure 5-15, but slightly lower than that of the "woody biomass to methanol to olefins" route.

5.6.3 Chlorine

Industrial chlorine is produced by the electrolysis of aqueous sodium chloride, called the chloralkali process. Besides chlorine, hydrogen gas and sodium hydroxide are also produced.

Three different types of electrolysis processes exist: membrane cell, mercury cell and diaphragm cell process. In the *membrane cell process*, the anode and the cathode are separated by an ion-exchange membrane, through which only sodium ions and a little water pass. In the *mercury cell process*, sodium forms an amalgam (a mixture of two metals) with the mercury at the cathode. The amalgam reacts with the water in a separate reactor called a decomposer where hydrogen gas and caustic soda solution at 50% strength are produced. In the *diaphragm cell process* the anode area is separated from the cathode area by a permeable diaphragm. The brine is introduced into the anode compartment and flows through the diaphragm into the cathode compartment. All three technologies produce hydrogen and caustic soda, the latter in different concentrations (diaphragm: 11%, membrane: 32%). In case of diaphragm or membrane technology, steam is used to increase the concentration of the caustic to market specifications (50%).

The share of mercury cell processes in the total chlorine production capacity has been steadily declining since the end of the 90s and producers across Europe are progressively moving towards membrane technology as this eliminates mercury emissions to waste water and to the atmosphere.

Recently installed new membrane cell capacities (2009) can e.g. be found in Spain (30 ktonnes per year) and Germany (430 ktonnes per year). Since 1984, no new plants based on the mercury cell technique have been built and only a few diaphragm cell plants.

The average electricity consumption for mercury cells is approximately 3,600 kWh per tonne, and for membrane and diaphragm cells about 2,800 kWh per tonne of produced chlorine. The overall EU average electricity consumption is 3,300 kWh per tonne of chlorine, whilst the lowest consumption figure is 2,460 kWh per tonne chlorine.

Little data could be found on measures applicable to existing chlorine plants. All data have been discussed within the topic team Technology and Innovation, involving also technology providers. For characteristics of new stock, mainly public sources have been used (UNEP, 2012) as well as best available technique reference documents (European Commission, 2011c). Validation has been done by the topic team Technology and Innovation.

For <u>existing chlorine plants</u>, three measures have been taken into account. Conversion of mercury cell plants to membrane cell technology, changing monopolar to bipolar membrane technology, and the retrofitting of membrane cell plants operating in 2010 to oxygen-depolarised cathodes technology (Figure 5-16).

When mercury processes are <u>converted to membrane cell technology</u>, electricity consumption is reduced by about 23%. However, additional steam is required to concentrate the caustic soda to 50%, as the produced caustic soda in membrane cell technology has a lower concentration (32%) than in mercury cell processes. The main driver for the conversion to membrane is a voluntary agreement and 100% conversion is expected to be complete by the end of 2020. The conversion to membrane cell technology is reported to cost 40–50% of the costs of a new membrane plant, totalling about \notin 500 per tonne of annual chlorine capacity.



Figure 5-16 Technical potential for energy efficiency improvements in existing chlorine plants in 2050. Economic feasibility is not taken into account

The <u>switch from monopolar to bipolar cells</u> applies only to membrane cell processes. Bipolar cells save energy by minimising the inter-cell voltage losses. The current share of monopolar in membrane cells is approximately 10%, which means the maximum applicability of this measure is about 5% of total 2010 chlorine capacity. Investments are estimated to be earned back in 5 years with 2010 industry electricity costs.

Oxygen-depolarised cathodes (ODC) can be used in membrane cell processes and reduce oxygen to produce hydroxide instead of converting water to hydrogen and hydroxide. This lowers the cell voltage by about 1 volt and translates to an energy saving of about 30%. The actual saving is lower, as oxygen with high purity needs to be produced, and hydrogen is no longer coproduced; producing the hydrogen elsewhere leads to a net increase of energy / feedstock use, but the conversion to power is no longer needed. A membrane cell plant using the ODC technique operated by Bayer and UHDENORA / Uhde with a chlorine capacity of 20 ktonnes per year was put into operation in summer 2011. Investment costs for the conversion to the ODC technique were reported to be in the range of EUR 70–100 per tonne of annual chlorine capacity (European Commission, 2011c).

For <u>new plants</u>, membrane cell technology is the best available technology and considered the baseline technology for future chlorine production. The power consumption of new electrolyser cells shows limited improvement from 2,550 kWh / t Cl_2 (commissioned in 2020), via 2,500 kWh / t Cl_2 (commissioned 2030) to 2,400 kWh / t Cl_2 (commissioned in 2050) whereas the steam consumption (needed for concentrating the produced caustic soda to market-grade) remains constant at 2 GJ / t Cl_2 . An alternative technology, also using brine as feedstock, is oxygen-depolarised cathodes (ODC), giving reductions of up to 30% of electricity compared to new conventional membrane plants (see ODC above).

In Figure 5-17, alternative chlorine production technologies are compared to the baseline technology, being the membrane cell.



Figure 5-17 Energy and feedstock use of new chlorine plants. The additional feedstock use is due to alternative hydrogen production in case of ODC technology. Data reflect final energy use in 2050

6 The road to 2050 – four scenarios

6.1 Europe on its way to 2050

The first half of the 21st century will likely see continued growth of the global economy with global power shifting from established industrial countries to currently emerging key economic regions. It is likely that interdependence between regions will continue to increase with expanding trade and information flows. The relative importance of Europe as an economic region is expected to decline, and Europe's population is expected to grow slowly between now and 2050 resulting in an ageing population. The economic growth worldwide will result in increased competition for resources.

How will Europe and more specifically Europe's manufacturing industry survive amid this increased competition? Will it be able to be a winning industry by providing goods and services to satisfy the increasing global demand for goods with production within Europe's borders? And how does this all relate to Europe's ambition to make a full transition to a low carbon economy in the coming decades? Will this ambition help to enable the manufacturing industry to remain competitive in the long run or will it perhaps create a low emitting Europe, meeting its material demands via high embodied carbon imports?

The future of the chemical industry is studied via four scenarios, which are described in Section 6.2. In Section 6.3 the CO_2 prices assumed in the different scenarios are explained, and in Section 6.4, the assumed energy prices are clarified. Finally, in Section 6.5, the methodology of bringing the information together is explained.

6.2 Four scenarios for the European chemical industry

The four scenarios explored differ in the energy and climate policy landscape in Europe and the rest of the world (level of ambition; CO_2 price; types of policies) and in projections on the energy prices and the speed of innovation. Based on these scenario descriptions, projections are made for the demand for and production of chemical products in Europe, and the resulting trade flows. Also, the development and uptake of the technologies discussed in Chapter 5 and the development of the mix for fuel, heat and power generation is projected for the four scenarios. The scenario projections are given in Chapter 7.

Table 6-1 gives an overview of the four scenarios, including two scenarios in which global action is absent and two scenarios in which international action is taken to keep global warming within the 2 °C limit:

- 1. In the <u>Continued Fragmentation</u> scenario, Europe continues with its current policies, but lowers the 2050 ambition to a 40% emission reduction in 2050 as compared to 1990 in the absence of global action against climate change.
- In the <u>Isolated Europe</u> scenario, the current fragmentation in energy and climate policies with a low global ambition continues, but Europe intensifies its policy ambitions striving for a 80% reduction in GHG emissions in 2050 as compared to 1990, even in the absence of a global agreement.
- 3. All key economic regions take action in the <u>Differentiated Global Action</u> scenario, with a global GHG emission reduction of approximately 50% between 1990 and 2050. The differentiated responsibilities result in an 80% GHG emissions reduction target for Europe. There is little convergence globally in the policy approaches followed.
- 4. In the <u>Level Playing Field</u> scenario, a global agreement is reached to mitigate climate change by reducing global GHG emissions by 50% between 1990 and 2050. Policies are chosen to ensure a level playing field for the global manufacturing industry via a uniform global carbon price signal.

A summary of the key input parameters is given in Annex 2.

Table 6-1	Description of scenario starting points
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	Continued	Isolated	Differentiated	Level Playing
	Fragmentation	Europe	Global Action	Field
Economy-wide GHG emission reduction target in Europe by 2050 compared to 1990	An economy-wide 40% target, 46% for industry.	An economy-wide 80% target, similar for industry.	An economy-wide 80% target, similar for industry.	Global ambition in line with 2 °C target (50% reduction), uniform global carbon price signal determines where abatement takes place.

Table 6-1	Description	of scenario	starting i	ooints ((continued)
	Beschiption	or section	Starting		(concinaca)

	Continued Fragmentation	Isolated Europe	Differentiated Global Action	Level Playing Field
Level of harmonisation	No global climate change agreement, continued fragmentation of worldwide energy and climate policies with low global and less ambitious EU ambitions.	No global climate change agreement, continued fragmentation of worldwide energy and climate policies. The EU is the only region with ambitious climate ambitions.	Global commitment in line with 2 °C target. Country ambition levels and policies differentiated with limited global convergence.	Global climate change agreement in line with 2 °C target. Uniform global carbon price signal, e.g. via fully linked emissions trading systems.
Main features of the energy and climate policies in Europe	The current EU Policy Initiatives are implemented. Actions beyond the current initiatives are not undertaken ⁴⁴ .	On top of the current EU policy initiatives, Europe's a is driven by carbon pricing for all sectors of the econ- all energy sources can compete on a market basis wi specific support measures for energy efficiency and r		trope's abatement the economy where t basis with no ncy and renewables.
Fossil fuel prices (Figure 6-4)	Strong increase in glo resulting in increasing No convergence in fo	Strong increase in global energy use resulting in increasing fossil fuel prices. No convergence in fossil fuel prices.		action, fossil fuel use re limited. No fuel prices.

⁴⁴ This scenario follows the Current Policy Initiatives scenario of the EU Energy Roadmap. The ETS cap is assumed to continue declining beyond 2020 as stipulated in legislation, however, with an effective domestic emission decrease lower than the linear decrease rate of 1.74% to result in a 50% cumulative decrease of actual emissions instead of 70% (European Commission, 2011b).

Table 6-1	Description	of scenario	starting	points	(continued)
	Description	or scenario	starting	points	(continued)

	Continued Fragmentation	Isolated Europe	Differentiated Global Action	Level Playing Field
Industrial electricity prices (Figure 6-4)	Electricity price of 107 € / MWh in 2030, stabilisation afterwards, continued differences in electricity price with rest of the world. Industry pays ~65% of average retail electricity price.	Electricity price of 132 € / MWh in 2030, stabilisation afterwards, continued differences in electricity price with rest of the world. Industry pays ~80% of average retail electricity price.	Electricity price of 96 \in / MWh in 2030, stabilisation afterwards, continued differences in electricity price with rest of the world. Industry pays ~60% of average retail electricity price.	Electricity price of 128 € / MWh in 2030, stabilisation afterwards; converging electricity prices globally. Industry pays ~80% of average retail electricity price.
CO₂ prices (in constant 2010 € / t CO₂) (Figure 6-1)	2030: 33 2050: 53	2030: 44 2050: 221	2030: 54 2050: 276	2030: 37 2050: 194

Table 6-1	Description	of scenario	starting	points	(continued)
	Description	or scenario	starting	points	(continueu)

	Continued Fragmentation	Isolated Europe	Differentiated Global Action	Level Playing Field
Scope of carbon pricing, allocation and differences with rest of the world	Existing ETS scope. Continued, but declining free allocation for direct emissions in the 2030–2050 period, no free allocation for power sector. No effective CO ₂ price signal in rest of the world.	ETS and non-ETS sectors have equal CO ₂ prices from 2020 onwards ⁴⁵ . No free allocation after 2020. No effective CO ₂ price signal in rest of the world.	ETS and non-ETS sectors have equal CO_2 prices from 2020 onwards. Continued, but declining, free allocation for direct emissions, no free allocation for the power sector CO_2 price difference taking free allocation of allowances into account with the rest of the world at most $30 \in / t CO_2$.	ETS and non-ETS sectors have equal CO ₂ prices from 2020 onwards. No free allocation after 2020. Uniform, global CO ₂ price signal.
Innovation	Low. Predominantly small incremental innovations without major development and deployment of breakthrough technologies.	Medium. Innovation in Europe is somewhat accelerated due to the high CO ₂ prices in this scenario.	High. Global action h stimulus on the deve deployment of break resulting in significar spillovers between w	as a positive lopment and through technologies It technology orld regions.

⁴⁵ This choice is made in line with the EU Energy Roadmap (European Commission, 2011a) where the same carbon value applies also to non-ETS sectors assuring cost-efficient emission abatement in the whole economy post-2020.

6.3 CO₂ prices and costs

CO₂ prices

The CO_2 prices for each of the four scenarios are detailed in Figure 6-1. The Continued Fragmentation scenario has the lowest CO_2 price, because this scenario has the lowest economy-wide GHG emissions reduction target (40% by 2050 compared to 1990). This scenario closely resembles the Current Policy Initiatives (CPI) scenario of the EU Energy Roadmap. This scenario forms the basis for the CO_2 price development in the Continued Fragmentation scenario.



Figure 6-1 Assumed development of the CO₂ price in the four scenarios

The Differentiated Global Action scenario has the highest CO₂ price of the four scenarios, and this scenario is quite similar to the EU Energy Roadmap's decarbonisation scenarios. The EU Energy Roadmap envisions several different decarbonisation scenarios. The "Diversified Supply" scenario forms the basis for the CO₂ pricing in the Differentiated Global Action scenario of this Roadmap. The Diversified Supply scenario, also discussed in the EU Commission's Low Carbon Economy roadmap, shows a decarbonisation pathway where all energy sources can compete on a market basis with no specific support measures for energy efficiency and renewables (European Commission, 2011a, page 27). It can thus be regarded as a technology neutral scenario without much direct technological support.

For the remaining two scenarios, Isolated Europe and Level Playing Field, the CO_2 prices are derived from the CO_2 price in the Differentiated Global Action scenario as detailed below.

In the Isolated Europe scenario, there are two factors which have an effect to decrease the CO₂ price:

- The rest of the world uses more fossil energy than in the Differentiated Global Action scenario. The resulting high fossil prices give Europe an additional incentive to reduce the use of fossil fuels. Consequently, a lower CO_2 price is required to reduce the European emissions to the 80% economy wide target.
- Under unilateral action on climate change, the international competitiveness of European industry is negatively impacted and as a result, lower European industrial production occurs compared to the Differentiated Global Action scenario, where there is global action on climate change, albeit differentiated. As a result, the economy-wide target can be reached with lower CO₂ prices as there are lower emissions from industry and the power sector due to lower levels of activity.

To account for these effects, a 20% lower CO_2 price is assumed in the Isolated Europe scenario as compared to the Differentiated Global Action scenario.

In the Level Playing Field scenario, a global 50% GHG emission reduction target in 2050 (as compared to 1990) is agreed with a uniform global carbon price signal, which determines where action is taken. As a result, abatement can take place at lower costs. To account for this, a 30% lower CO_2 price in the Level Playing Field scenario is assumed compared to the Differentiated Global Action scenario. The resulting CO_2 prices are shown in Figure 6-1.

These prices are also used in the economic assessment of emission saving measures of which the results are described in Section 7.3. The balance between investment costs and the resulting GHG emissions reduction and energy savings determine the profitability of the measures. Some measures become putatively profitable as a result of the higher CO_2 prices (and for some cases higher energy prices) compared to today. However, compared to lower CO_2 and energy prices, these measures still result in an additional burden as compared to an environment with low CO_2 and energy prices, due to necessary investments and labour costs. Thus, the development of energy or GHG bills does not reflect real additional burdens. It is thus important to compare the effective CO_2 cost burden on the European chemical industry in comparison with the rest of the world to assess the impact of the CO_2 price signal on competitiveness.

CO₂ costs

 CO_2 costs are important to investigate, as is the difference in the CO_2 costs between Europe and the rest of the world. CO_2 costs arise when industry has to pay for emissions and the costs are therefore dependent on the level of allowances to emit GHGs allocated at no charge. Figure 6-2 shows the difference in CO_2 costs between the European chemical industry and the rest of the world. Differences in CO_2 costs appear after 2020 and increase depending on the scenario with the largest difference in CO_2 costs between Europe and the rest of the world observed in the Isolated Europe scenario. In

contrast, the Level Playing Field scenario is characterised by similar CO_2 prices and costs around the world so the difference is always zero through the time period studied.

The Continued Fragmentation scenario assumes no CO_2 price signal in the rest of the world. However, this scenario has the lowest economy-wide target, so the differences in CO_2 costs are lower than the Differentiated Global Action scenario. In the Isolated Europe scenario, industry does not receive free allocation beyond 2020 and it is assumed that there is no CO_2 price signal in the rest of the world. The CO_2 cost difference with the rest of the world in this scenario is equal to the CO_2 price signal which rises to over $200 \notin / t CO_2$ in 2050.

In the Differentiated Global Action scenario, it is assumed that (declining) free allocation in Europe results in a smaller difference in CO_2 costs between Europe and the rest of the world, and that the difference does not exceed $30 \in / t CO_2$.



Figure 6-2 Assumed difference in the CO₂ costs felt by industry between the EU and the rest of the world

6.4 Energy price developments

The prices in the EU Energy Roadmap (European Commission, 2011b) forms an important basis for the prices assumed in the different scenarios. An overview of sources used to determine the prices is given in Table 6-2.

	Continued Fragmentation	Isolated Europe	Differentiated Global Action	Level Playing Field
Coal	EU Energy	Roadmap	EU Energy	Roadmap
Oil	Current Policy In	itiatives scenario	Decarbonisation scenario	
Gas	in line with the IEA's Energy Technology Perspectives 2012 (IEA, 2012c) 6 DS scenario prices		in line with the IEA's Energy Technology Perspectives 2012 (IEA, 2012c) 2 DS scenario prices	
Electricity	EU Energy Roadmap Current Policy Initiatives scenario	EU Energy Roadmap Diversified Supply scenario Adjustments for different fossil fuel prices, CO ₂ price and cost distribution (see below)	EU Energy Roadmap Diversified Supply scenario Adjustments for different cost distribution (see below)	EU Energy Roadmap Diversified Supply scenario Adjustments for different CO ₂ price and cost distribution (see below)
Wood pellets	APX / ENDEX and Ecofys expert opinion			
Ethanol	Platts (2012), IEA (2012c) and OECD / FAO (2011b)			
Geothermal heat	IPCC (2011), IEA (2010a) and IEA (2010b)			

Table 6-2Overview of the data sources for the energy prices

Fossil fuel prices

The prices of fossil resources (oil, natural gas and coal) were all taken from the EU Energy Roadmap:

- The prices in the Continued Fragmentation and Isolated Europe scenarios were both taken from the EU Energy Roadmap's Current Policy Initiatives (CPI) scenario. The underlying assumption in this scenario is that globally no additional climate action is undertaken up to 2050 beyond current policies. Therefore use of fossil fuels continues to rise steeply with an increasing effect on the price. For the Isolated Europe scenario the relatively small impact of the reduced demand for fossil fuels in Europe as a consequence of the unilateral high ambitions in Europe is ignored. These prices are in line with the 6 DS scenario in IEA's Energy Technology Perspectives (IEA, 2012c) which also is largely an extension of current trends. By 2050, global energy use almost doubles (compared with 2009) and total GHG emissions rise even more. In the absence of efforts to stabilise atmospheric concentrations of GHGs, average global temperature rise is projected to be at least 6 °C in the long term.
- The fossil fuel prices in the Differentiated Global Action and Level Playing Field scenarios were both taken from the EU Energy Roadmap's decarbonisation scenarios. Here the underlying assumption is that the rest of world's ambition leads to a reduction of global emissions of 50% by 2050 compared to 1990. This leads to a relatively low global coal / oil / gas demand and price in both scenarios. These prices are in line with IEA's Energy Technology Perspectives (IEA, 2012c) 2 DS scenario⁴⁶.

In this Roadmap, unconventional gas was not studied separately (refer to Box 6-1).

⁴⁶ This scenario describes an energy system consistent with an emissions trajectory that recent climate science research indicates would give an 80% chance of limiting average global temperature increase to 2 °C. It sets the target of cutting energy-related CO_2 emissions by more than half in 2050 (compared with 2009) and ensuring that they continue to fall thereafter.

Box 6-1 Shale and other unconventional gas in this Roadmap

Unconventional gas is an overarching term for tight gas, shale gas, coalbed methane and methane hydrates. Unconventional gas has led to changes in global natural gas supply and trade. In the USA, the rapid exploration of shale gas and the subsequent overcapacity of natural gas supply have led to low natural gas prices and have created a significant competitive advantage for industry in the USA. The European potential for recoverable unconventional gas is estimated to be in the same order of magnitude as conventional gas resources (IEA, 2012d). This is significant, but it is unlikely that exploration of these reserves will change the import dependency regarding natural gas. According to IEA (2012d), the import dependency for natural gas in 2035 in Europe would be 86% in a low unconventional scenario as compared to 74% in a high unconventional gas scenario. Environmental concerns related to unconventional gas concern the large volumes of water used, methane emissions and potential pollution due to the chemicals used in the exploration. Exploration of shale gas in Europe and globally should therefore pay appropriate attention to these environmental issues.

The impact of unconventional gas development in Europe on the price of gas for Europe is difficult to assess, because the long term natural gas equilibrium price is determined by many factors, including developments in the demand and supply in other regions of the world, e.g. China. Exploration and production of shale gas in Europe will have a decreasing impact on long-term natural gas prices in Europe. This also holds for an improved natural gas trade infrastructure in Europe and strengthened natural gas trade relations (Liquefied Natural Gas pipelines and terminals, natural gas trade with Russia etc.)

In this Roadmap, a shale gas scenario is not studied explicitly, but natural gas import prices from the EU Energy Roadmap (European Commission, 2011b) are used as a basis for energy price projections without detailing the exact differences with regions outside Europe. However, the current energy and feedstock price differences between Europe and certain regions of the world (including shale gas in the US and associated gas in the Middle East) are important drivers for the negative outlook for the chemical industry in three of the four scenarios studied. Measures such as those described above (accelerating the sustainable exploration and production of indigenous shale gas and further investing in natural gas trade relations) can contribute to a more competitive position of the European chemical industry in terms of energy and feedstock costs.

Historic gas and oil prices

In Figure 6-4, historic oil and gas prices are shown for comparison with their respective range that is assumed for future years in the different scenarios. The figure clearly shows that the cost of oil and gas increased significantly over the past couple of years and is not expected to decrease back to the values in the nineties. More importantly, policy costs, not included in Figure 6-4, add substantial costs to the levels shown in this graph, especially in the scenarios at the lower ends of the shown ranges (refer to Figure 6-5).



Figure 6-3 Historic and projected oil and gas import prices at constant 2010 €⁴⁷ with historical prices from BP (2012); future prices give the range of import prices over the scenarios excluding policy costs

Industrial electricity prices

Currently, in the market the electricity end-user (retail) prices are determined by the wholesale price plus fixed costs such as transmission, distribution and balancing costs. The wholesale price is related to the variable costs for the marginal power station to meet demand. Variable costs are largely dominated by fuel costs, so renewable electricity and nuclear have zero or low variable costs, and fossil fuel-fired power stations have higher variable costs. The EU Energy Roadmap mentions that price formation for electricity might change in future, because of the penetration of renewable electricity generation with no variable costs. However, the marginal cost concept can still play an important role up to 2050, because electricity costs with carbon capture and storage (coal and gas fired) still have significant variable costs from fuel usage. It is well conceivable that these costs will be supplemented, more than today with costs to cope with highly intermittent renewable electricity (costs for back-up capacity, storage, more interconnectors and demand response management). Projecting the electricity price in general is for these reasons subject to large uncertainties.

Different types of consumers pay different end-user electricity prices. In the EU Energy Roadmap Current Policy Initiatives scenario, industry is assumed to pay a price that is 65% of the average electricity end-user prices. In the Diversified Supply scenario, industry is assumed to pay a price of

 $^{^{47}}$ 2011 \$ prices in source converted to 2010 € with inflation rate correction of 3.1% and EUR/USD exchange rate of 1.34

approximately 70% of the average electricity end-user prices. Others, such as households, pay more than these industrial end-user prices. These higher prices for others can be explained by the higher transaction and distribution costs per supplied kWh, but also because a larger share of e.g. levies to support renewable electricity is passed on to households as compared to industry.

For the <u>Continued Fragmentation</u> scenario in this Roadmap, electricity prices as used in the EU Energy Roadmap Current Policy Initiatives scenario are assumed. For the <u>Isolated Europe</u>, <u>Differentiated Global Action</u> and <u>Level Playing Field</u> scenarios, the Diversified Supply Scenario of the EU energy roadmap is used as a basis. In this scenario, a mix of different electricity options is used, mainly driven by CO₂ prices / values. The underlying modelling in the EU Energy Roadmap assumes that all costs entailed by power generation are recovered through electricity end-user prices.

For the Isolated Europe and Level Playing Field scenarios, the average electricity end-user price was corrected for the different CO_2 prices and, for the Isolated Europe scenario, a further correction was made for the different fossil fuel prices, but the mix of electricity technologies used has not been adjusted.

To reflect the uncertainty regarding the price of electricity for industry as compared to the average, the following adjustments were made: In Isolated Europe, a 15% higher electricity price for industry is assumed as compared to the EU Energy Roadmap, reflecting the risk that ultimately industry has to pay a more significant share of the fixed costs related to the transition to a decarbonised electricity sector. The same assumption is made for the Level Playing Field scenario, assuming that industry in key competing regions outside Europe pays a similar electricity price. The price of electricity in these scenarios is ~80% of the average electricity price. For Differentiated Global Action, a 15% lower electricity price for industry as compared to the EU Energy Roadmap is assumed, which could be the situation if some measures were taken to support industry in remaining competitive in terms of electricity prices.

Biomass prices

As a proxy for biomass prices, price projections for industrial grade wood pellets and ethanol were made:

- IEA (2011c) and other studies state that, technically, the supply of pellets can meet the demand under the right conditions (sustainability, standards, transparency) and production costs are relatively independent of costs of fossil fuels. The 2010 cost of pellets was based on real prices, with additional costs for transport and for the complexity of use of biomass in comparison with gas, while projections for the future were made in the context of the topic team Markets.
- The dominant feedstock for ethanol over the next decade will be sugar. After that, as second generation technologies become viable, any woody biomass could be used, and ethanol prices could decouple from sugar prices. Ethanol prices in 2010 are taken from Platts (2012).

Forecasts for future years are taken from IEA (2012c) and OECD / FAO (2012). Ethanol production costs depend on fossil fuel prices, since a significant share of ethanol is currently made from fertiliser and fuel intensive food crops like maize in the USA. As second generation conversion technologies (cellulosic ethanol) become viable after 2020, prices are expected to decouple from fossil fuel prices. Until 2020 there is still an import duty on ethanol.

 Many different biomass sources could be used, which means that in reality biomass prices will be a range rather than the one absolute number that is used. For globally traded biomass commodities (such as pellets and ethanol) a market price exists, but some forms of biomass (for example wet biomass like manure or slurry) are sold in local markets, with different prices depending on location, sometimes even negative prices are seen, for example for certain wastes.

Box 6-2 Ethanol pricing

Ethanol demand (currently about 70 Mtonne per year) is driven mainly by the transport sector (currently about 90% globally). Alcoholic beverages, solvent applications and chemical raw material are minor uses for ethanol (about 4% each). To avoid the need for a full and complex model of future ethanol market price mechanisms from supply / demand and policy driven influences (oil prices, legislation to encourage biomass in fuels, global sustainability and agricultural policies) production costs are used as a proxy for the market price of ethanol in this Roadmap. A similar approach was followed for pellets. Only minor consequences of this choice are expected until at least 2030. For 2050 it must be taken into account that a real market price approach where biomass prices remain strongly coupled with fossil fuels prices, could lead to lower market shares of biomass and ethanol-based production routes.

Geothermal heat prices

The last energy source taken into account in this Roadmap is geothermal heat. For geothermal heat, specific investment costs, O&M and expected capacity factor developments are considered (IPCC, 2011). Specific investments are based on calculations by Ecofys taking the average costs of three types of drilling technologies, together with an expectation for reduction in drilling costs (IEA, 2010a).

European energy prices

The resulting energy prices in Europe are summarised in Figure 6-4 and Figure 6-5, which show the energy prices including distribution costs and energy taxation, excluding and including CO_2 costs respectively.



Figure 6-4 Prices of energy sources in Europe in the different scenarios excluding CO₂ costs in 2010 €



Figure 6-5 Prices of energy sources in Europe in the different scenarios including CO₂ costs in 2010 €
Comparison with international energy prices

Prices for oil and coal are assumed to be relatively equal around the world, although differences can exist. Gas and industry electricity costs vary more in different regions, because gas is more difficult to transport (it requires energy intensive and expensive liquefaction before transport and regasification after the transport), while the industry electricity costs depends on the technologies used to produce the electricity, the prices of required resources, power transport capacity and power generation capacity. For both, local market regulations and monopolies are important factors.

Biomass prices differ around the world and even within Europe to varying degrees, depending on the type of biomass. This has not been assessed separately in this Roadmap.

The assessment of international differences in fossil fuel and electricity prices is based on IEA (2012a), IEA (2012d) and Ecofys expert input. Prices for fossil fuels and electricity are lower in some key competing countries. The USA, due to the presence and exploration of unconventional gas, Canada, and the Middle East are regions with significantly lower fuel, feedstock and electricity prices. This was taken into account by assuming continued differences in fossil fuel and electricity prices in all scenarios over the projected years, except for the Level Playing Field scenario, where converging prices are assumed.

6.5 Role of carbon, energy and feedstock prices

The methodology used to arrive at projections of demand for chemical products, the production in Europe and the uptake of technologies resulting in the energy and GHG emission pathways to 2050 is summarised in Figure 6-6.



Figure 6-6 Schematic of used methodology

An Excel-based tool was used for the scenario projections, following a step-wise approach:

- 2010 is used as base year for the analysis (using the data shown in Chapter 2) and three future years are assessed: 2020, 2030 and 2050. Intermediate years were not studied.
- First, the demand for chemical products for the five subsectors was derived for the future years and the different scenarios.
- Then, EU production of the five subsectors was derived for the future years and the different scenarios, also taking into account, where relevant, increasing shares of recycling and bio-based production of chemicals.
- For the products studied individually (cracker products, ammonia, chlorine, nitric acid), demand and production growth is assumed to be identical to that of the subsector in which the product belongs.
- Combining demand and production yields the trade ratio (net effect of import and export) for the future years.

- EU production in plants that already existed in 2010 was established by assuming that, depending on the subsector, 2–4% of capacity is taken out of operation each year, and the remaining capacity is debottlenecked with 1% relative to 2010 each year. Additionally, it has been assumed that in 2010, due to the financial crisis, there was 5% spare capacity.
- These assumptions yield an estimate of the new plants required for the 2020, 2030 and 2050 production.
- For subsectors, a generic approach was followed for the improvement of plants operating in 2010. No autonomous improvements in efficiency were assumed, but instead, developments have been assessed against a frozen efficiency reference for the base year 2010. This is close to industrial reality, where all improvements made depend on efforts and investments.
- For the four products studied in detail (cracker products, ammonia, chlorine, nitric acid), the applicability of energy efficiency and GHG abatement measures were studied in more detail. The implementation rate of measures / choices between processes was determined using an Internal Rate of Return (IRR) criterion of 12%⁴⁸, at an economic lifetime of 15 years. The IRR criterion of 12% has been used to stay in line with the Commission's Energy Roadmap, although the lifetime of 15 years is shorter. Industry typically uses higher IRR criteria; the impact on the results for these products is expected to be limited.
- For the new stock required in 2020, 2030 and 2050 following demand and projections, the energy and GHG emissions intensity was determined. For subsectors, again a generic approach was followed, while specific technologies were established and compared against each other using the abovementioned IRR criterion for the four products studied individually. In all cases, improvement of the energy efficiency, after new stock was built, was taken into account with a generic factor equal to 90% of the assumed improvement of new stock over time.
- The use of CCS for ammonia, cracker products and the subsectors was assessed separately.
- The total energy and GHG pathways for the chemical industry were determined by adding the results for the individual subsectors and products.
- Enabling of reductions of emission in other sectors is determined separately (Chapter 4 and 8).

⁴⁸ For the production of cracker products in plants with already existing stock, investment data was not available for several of the measures. No IRR criterion was used for cracker products, but the implementation of measures was established based on expert judgements in the context of the topic team Technology and Innovation.

7 Results – reducing the carbon intensity of the chemical industry

7.1 Energy and emission profile for the chemical industry up to 2050

Based on the narratives outlined in the previous chapter, projections were developed for the demand for the chemical products from the five subsectors studied in this Roadmap, the production of these chemicals in Europe and the resulting trade patterns. Combined with assumptions on the uptake of the various energy efficiency and GHG reduction options discussed in Chapter 5 under the conditions as outlined in the scenario narratives, this results in the energy and GHG emission profile of the European chemical industry as given in Figure 7-1 and Figure 7-2.



Figure 7-1 Final energy use and energy efficiency improvements in the European chemical industry 2010–2050. Upper lines reflect energy use with projected production and 2010 energy intensity



Figure 7-2 GHG emissions and contributions of GHG emissions reduction from 2010 – 2050. Upper lines reflect GHG emissions with projected production and 2010 GHG emissions intensity⁴⁹

In these graphs, the upper lines represent the development of, respectively, the energy use and GHG emissions taking the projected production by subsector and product, but assuming 2010 levels of energy and GHG emissions intensity. Energy efficiency improvements result in lower actual energy use compared to this frozen intensity reference (the lower line in Figure 7-1) and contribute, with several other options, to lower GHG emissions (the lower line in Figure 7-2).

Differences in production levels are an important factor in these graphs. Reduced European production leads to more import of chemical products. The level of GHG emissions reduction achieved in Europe would, in case of increasing imports, be achieved at the expense of increased emissions elsewhere. This would happen with no overall reduction in global GHG emissions or even a potential increase as is discussed below.

⁴⁹ In line with the scope of this project (Section 1.4), emissions relate to scope 1 (direct emissions) and scope 2 (direct emissions related to the production of purchased electricity and bought heat) only and thus exclude upstream emissions from fossil fuel exploration and production, emissions from the cultivation of biomass (e.g. those related to indirect land use changes) and emissions related to end-of life treatment of chemicals outside the scope of the European chemical industry.

Total energy use decreases slightly in the Continued Fragmentation and Differentiated Global Action scenarios up to 2030. The same is valid for the Isolated Europe scenario, but this scenario shows a sharp decline in energy use beyond 2030. Energy use is growing by 1% from 2010 to 2030 in the Level Playing Field scenario, caused by the increased European production in this scenario and a continued net export position of the European chemical industry. In all scenarios, the share of renewable energy sources is increasing, mostly so in the Level Playing Field scenario.

Three options (energy efficiency improvements, a change in the fuel mix for heat generation and N_2O emission abatement) together, which remain under the control of the chemical industry itself, have the potential to reduce emissions intensity in 2050 by about 55% as compared to a situation without further improvements in the greenhouse gas intensity beyond 2010. For 2030, this is approximately 40%. Compared to 2010 levels, these options would reduce greenhouse gas emissions by 15% in 2030 with stabilisation around these levels towards 2050, building on an achieved reduction of 50% in 2010 compared to 1990, as previously estimated in other studies.

The Roadmap results show that less reduction in GHG emissions intensity of the European chemical industry would be realised in the Continued Fragmentation scenario. In this scenario reductions in GHG intensity would be approximately 30% in 2030 and less than 50% in 2050, compared to 2010 (see Figure 7-2). The reduction in GHG emissions intensity is less in this scenario compared to the Level Playing Field scenario due to, among other reasons, a limited growth and relocation of production to outside Europe. Higher absolute GHG emissions reductions would be achieved by these options in Europe under such and other scenarios of fragmented action, up to 25% absolute GHG emissions reduction in 2030 compared to 2010. However, this would happen at the expense of relocation of production to outside of Europe, with no overall reduction in global GHG emissions or even a potential increase.

The graphs show that it is possible to decouple energy use from GHG emission reduction, while it is not possible to decouple production growth and energy consumption in the long term. This is important in view of the discussion on absolute energy saving versus relative energy efficiency targets (see also Chapter 3).

In this chapter, the outcomes of the scenario analyses are analysed in more detail, by focusing on the production patterns that are an important explanation of the energy and GHG emission development (Section 7.2), the role of feed switches (not shown in the graphs above, Section 7.3.1) energy efficiency (Section 7.3.2), the role of heat source changes (Section 7.3.3) and the role CCS and N_2O emission abatement (Section 7.3.4). The role of the decarbonising electricity sector, which also significantly contributes to the GHG emission abatement in the scenarios, is an inherent consequence of the assumptions on the electricity sector as outlined in Chapter 6 and is not further discussed.

7.2 Demand, production and trade

Methodology

The demand for chemical products in the different scenarios was derived in several consecutive steps. First of all, GDP assumptions were determined. As a starting point, the annual GDP growth per annum was determined for the <u>Continued Fragmentation</u> scenario, which has the lowest level of ambition on climate policy. For this scenario, GDP growth from 2010 to 2050 was chosen in line with the EU Energy Roadmap 2050 (European Commission, 2011b) but corrected for the slow recovery in GDP projections for 2010–2020. Therefore, the annual GDP growth projection is 1.4% between 2010 and 2020, 1.7% from 2020 to 2030, and 1.5% between 2030 and up to 2050.

These annual GDP projections formed the basis for assumptions by the topic team Markets on growth of the seven sectors consuming chemical products⁵⁰, using projections of VCI-Prognos (2012) and expertise of the topic team Markets. The demand for chemicals was subsequently derived from an input / output model, which connects the required chemical input to the projected output in the seven consuming sectors. For example, based on certain GDP assumptions, the industrial sectors (i.e. Agriculture, Construction, Mobility, Energy, Other Industries or Services) are supposed to produce a certain output. The input / output model specifies the chemical inputs from the five subsectors (Petrochemicals (incl. intermediates), Basic Inorganics, Polymers, Specialty Chemicals and Consumer Chemicals) that are needed to produce this output. The private households sector is also directly purchasing goods from the chemical industry. This is also considered in the input / output model.

For the remaining three scenarios (Isolated Europe, Differentiated Global Action and Level Playing Field), adjustments have been made to the growth projections (annual GDP) for the seven consuming sectors as well as in the input of chemical products into these sectors as compared to the Continued Fragmentation scenario, to reflect some of the key characteristics of these scenarios. For example, the consuming sector classified as "Other Industries", is assumed to have less growth in the Isolated Europe scenario because these industries will partly relocate outside Europe. Similarly, the demand for chemical products in the Construction sector is assumed to be higher in the three scenarios with a high European decarbonisation ambition to reflect more significant energy efficiency gains in this sector using innovative chemical products. This leads to some, albeit limited differences in demand for chemical products between the scenarios. Generally, demand for chemical products is highest in the Isolated Europe scenario⁵¹.

⁵⁰ Agriculture, Construction, Mobility, Energy, Other industries, Services, Private consumption/Households

⁵¹ Total demand for chemical products ranges from 700 billion Euro in 2050 in the Isolated Europe scenario and 900 billion Euro in the Level Playing Field scenario, as will be shown later on.

This roadmap does not use a comprehensive dynamic macroeconomic model. Therefore most effects have been modelled only as direct effects, neglecting further macro-economic feedback processes. For example: a lower (higher) production in a certain industry would have some negative income and labour market effects which would be decrease (increase) disposable income of private households' consumer spending and therefore negative (positive) spill-over effects to other industries. As a result, the negative effects of the Isolated Europe scenario are likely to be underestimated and likewise the positive effects of the Level Playing Field scenario.

In order remove the effect of product price developments and therefore energy prices, the resulting data on production and demand levels is based on constant $2010 \in$ prices.

Projected production levels from the European chemical industry to meet the demand projections were then analysed. For each scenario the current production capacities, the current net trade position and trend developments in trade that were already recognisable in the past were taken into consideration. Based on this information, production trends for the future were modified in the scenarios according to its characteristics and judgement by the experts in the topic teams and the key factors listed below. Demand for chemicals is one factor, but whether or not demand is met by production in Europe or by production outside Europe is mainly driven by the competitive position of the European chemical industry as compared to the rest of the world. Focusing on energy and climate, key drivers these are:

- **Energy and feedstock prices.** Currently, energy and feedstock costs are higher in Europe as compared to many areas in the world. Notable examples are the existence of cheap associated gas as feedstock for the chemical industry in the Middle East and the recent shale gas boom in the USA, resulting in fuel and feedstock prices that are well below those in Europe.
- **Differences in policy costs.** The difference in GHG and other energy policies between the EU and non-EU results in differences in policy costs. These costs can be the direct costs of e.g. a CO₂ price signal (coming directly to industry for the fuels used or indirectly as part of the electricity) or can be more indirect costs related to e.g. the pass through of subsidies for renewable electricity to consumers.
- Existence of integrated value chains. The subsectors of the chemical industry are heavily integrated. Products of the petrochemical industry are used for the production of polymers, specialties and consumer chemicals. In many cases, these products are produced at integrated sites resulting in efficiency and supply chain advantages, as was stressed in several of the regional workshops (Section 1.4). Relocation of the basic chemical industry (Petrochemicals, Basic Inorganics) therefore likely causes the relocation of more downstream activities.

Table 7-1 summarises the key scenarios assumptions for these three drivers and the key direction of these drivers (positive or negative) over time.

Table 7-1	Scenario assum	ptions on kev	competitiveness	differences
			een petiti en eeu	

Scenario	Energy price differences EU versus rest of the world	CO ₂ cost differences EU versus rest of the world	Impact on integrated value chain
Continued Fragmentation and Differentiated Global action	- Price differences existing in 2010 with the rest of the world remain	- CO_2 price signal between Europe and rest of the world increasing over time to ~30 € / t CO ₂ in 2050	- Negative impact on production for basic chemical industries also affects Specialty Chemicals and Consumer Chemicals
Isolated Europe	- Price differences existing in 2010 with the rest of the world remain	 CO_2 price signal between Europe and rest of the world increasing over time to over 200 \in / t CO_2 in 2050	 Negative impact on production for basic chemical industries also affects Specialty Chemicals and Consumer Chemicals
Level Playing Field	+ Energy and feedstock prices and industry electricity costs converge over time	+ A similar CO ₂ price signal across the world	+ Full integrated value chain remains in Europe

The extent to which the negative differences as compared to the rest of the world result in relocation of production from Europe to other regions of the world, depends on many factors. A distinction can be made between production leakage (in the short term, production in Europe is more expensive compared to elsewhere) and investment leakage (the expected overall return on investment in Europe is lower as compared to other parts of the world). In the last decade, production and investment leakage resulting from unilateral carbon pricing (i.e. carbon leakage) has been studied in quite some detail (e.g. Burniaux et al, 2008; Dröge, 2009; Manders and Veenendaal, 2008; Grubb et al., 2009; Summerton, 2010; Böringer et al., 2010; OECD, 2012; Carbon Trust, 2010; Varma et al., 2012). Most empirical studies focus on production leakage only driven by CO₂ price, which induce differences in production costs often combined with or without certain demand elasticities (i.e. the preference of consumers for domestic products) and arrive at typical production leakage rates of 2–5% for the timeframe up to 2030 for the European chemical industry (European Commission, 2011a; Hübler and Löschel, 2012).

Analyses done in this Roadmap show that for bulk basic chemicals such as those studied individually in this Roadmap (cracker products, ammonia), CO_2 prices of $10-100 \in /t CO_2$ (or differences in CO_2 costs in this order of magnitude versus other regions) would cover the additional transportation costs required from production abroad, assuming the same average efficiency of plants in Europe and outside Europe. These prices are reasonable estimates for the CO_2 price that would trigger investments in new production capacity taking place mainly outside Europe⁵². These trigger price differences are by far exceeded in the Isolated Europe scenario, but also the Continued Fragmentation and Differentiated Global Action scenarios arrive at cost differentials with the rest of the world in 2030 that are close or beyond these trigger prices. On the other hand, the negative impact of CO_2 prices is limited by the desire for security of supply, growing transport costs and the political stability and predictability in the EU in comparison with many other regions.

The negative outlook for the basic chemical industries (Petrochemicals, Basic Inorganics, bulk polymers) in some of the scenarios is further strengthened by existing differences in energy and feedstock prices with certain regions of the world.

For the more downstream chemical sectors the energy and feedstock costs are a smaller part of the sales price. However, due to the highly integrated value chain of the European chemical industry, the negative outlook for the basic chemical industries will also have a negative impact on the downstream chemical sectors. This negative impact on the European chemical industry is partly offset through innovation from innovation clusters present in the EU, made possible by highly integrated production sites, established infrastructure, technological advanced plants and a skilled workforce.

Demand and production projections were made for the five subsectors as a whole. No separate projections were derived for the individual products groups studied in more detail in this Roadmap. Demand and production growth for cracker products are thus in the calculations assumed to be identical to that of the subsector Petrochemicals, and the demand and production growth for ammonia, chlorine and nitric acid are in the calculations assumed to be identical to that of the Basic Inorganics subsector. This is a simplification, because in reality, individual products within a subsector will see different growth patterns depending for example on how they are integrated with their upstream and downstream value chain and on how easily they are traded. This is, in particular, true for the Basic Inorganics subsector that consists of quite a variety of different product groups.

In addition to calculating the resulting trade ratio for the various scenarios, also the effect of this trade on emission indirectly imported or exported from Europe was calculated by multiplying, per subsector, the net import or export with the European emissions intensity as shown in Figure 7-2, expressing it as a percentage of the actual emissions from the European chemical industry itself.

 $^{^{52}}$ The use of transportation costs based estimates to project production leakage is more difficult, because the form of the demand and supply curve, the relative efficiency position of the various plants and the situation regarding global capacity all play a significant role here. However, for judging the profitability of investments, a CO₂ price level that overcomes the additional transportation costs, all else being equal, can be considered as a very relevant parameter to project investment carbon leakage.

Resulting pattern

In Figure 7-3 to Figure 7-8⁵³, the resulting projections for demand and production of the five subsectors and the European chemical industry studied in this Roadmap are given as well as the compound annual growth rates (CAGR). The projections are based on value in constant 2010 \in . The difference between production and demand provides insight into the development of the net trade in chemical products in each of the scenarios.





Figure 7-3 Demand and production patterns for the four scenarios, Petrochemicals

⁵³ The total sales for the European Chemical Industry do not fully match with the sum of subsector sales. This is because the increased share of bio-based production results in lower sales between the Petrochemicals and other subsectors, because implicitly, the full bio-based production chain is assumed to take place in the subsectors where the final product is produced. In the sales figures for the total European chemical industry, these sales have been added in order not to distort the overall energy and emissions intensity development resulting from this changing subsector structure.























Figure 7-7 Demand and production patterns for the four scenarios, Consumer Chemicals



Figure 7-8 Demand and production patterns for the four scenarios, European chemical industry

The impact on the net trade ratio is significant. It is negative for the Isolated Europe scenario and neutral to positive for the Level Playing Field scenario. The other two scenarios are in between; they show comparable performance. An overview of the impact is given in Figure 7-9. Whereas the trade surplus in 2010 was \in 42 billion, the scenario shows a range between an increase of the surplus to \in 120 billion and a deficit of \in 130 billion in 2050 in constant prices.

Figure 7-10 gives the trade ratio, where for each product and subsector, the net trade has been multiplied with the emissions intensity of the European chemical industry as shown in Figure 7-2. This ratio differs from that for the European chemical industry in Figure 7-9, because the trade is weighted by the emissions intensity per subsector. For 2010, this results in net exported emissions of less than 5% as compared to an overall export ratio of about 10% due to dominance of the less emissions intensive subsectors in the net export position. The figure clearly shows the negative trend with respect to imported emissions in all scenarios with a competitive disadvantage for Europe as compared to the rest of the world. This clearly shows that the absolute reduction of emissions in Europe (which is for the 2030 timeframe higher for the <u>Continued Fragmentation</u>, <u>Isolated Europe</u> and <u>Differentiated Global Action</u> scenarios as compared to the <u>Level Playing Field</u> scenario, see Figure 7-2) is achieved at the expense of increased emissions elsewhere. Globally, this would happen with no overall reduction in global GHG emissions or even a potential increase. This is because for the <u>Isolated Europe scenario</u> in particular, the approach of taking the European emissions intensity as the basis for calculating the emission effect of trade is a conservative one. In practice, the emissions





Figure 7-9 Net trade ratios for the five subsectors and the European chemical industry as a whole



Figure 7-10 Net emission trade ratio for the European chemical industry in the four scenarios

That the total emissions from total consumption (including imports) can give a different picture on the development of emissions over time, compared to an analysis of domestic emissions only, is confirmed by studies such as Policy Exchange (2010) and CBS (2012). Both studies show, for the UK and the Netherlands respectively, an increase in consumption related emissions in the past decades in contrast to a decline in the domestic emissions, illustrating the importance of focusing on approaches to sustainable consumption rather than on production only.

Discussion

The competitiveness of the European chemical industry is damaged under all scenarios where it continues to have higher energy and policy costs in comparison to other regions. In the Continued Fragmentation and Differentiated Global Action scenarios, energy price differences with the rest of the world remain, and CO_2 cost differences increase over time. The direct CO_2 costs in the Continued Fragmentation scenario can already be estimated as \in 1.7 billion per year of direct CO₂ costs alone in 2030 and \in 3.1 billion in 2050, even excluding CO₂ and other policy costs passed on via the electricity bill⁵⁴. As a result, the sectors with highest energy and CO₂ costs per unit of sales (Petrochemicals, Basic Inorganics, bulk polymers) show limited growth, especially in the 2030–2050 timeframe when decreasing investments in new capacity in these sectors become apparent. In the Isolated Europe scenario, CO_2 costs differences increase steeply over time, especially for the 2030–2050 timeframe. As a result, this leads to an overall negative growth of the European chemical industry in the period beyond 2030. The negative outlook for the basic chemical industry in each of these scenarios also negatively influences the outlook for the more downstream subsectors of the chemical industry, because these industries benefit less from the positive impact of a fully integrated value chain in Europe. As a result, the trade balance also worsens for these subsectors. Nonetheless, most downstream subsectors continue to grow in terms of production value in all scenarios, due to innovation and the close proximity to clients in the EU.

It should be stressed that the subsector developments as shown are also applied to the products individually studied in this Roadmap (i.e. ammonia, cracker products, chlorine, and nitric acid). This simplification, combined with assumptions on typical stock turnover rates (assuming a typical lifetime of 50 years for production plants for basic chemicals with some debottlenecking over time), implies that in the calculations in this Roadmap, for each of the scenarios, investments in new installations take place for ammonia and cracker products. This is despite the competitive disadvantages assumed in the Continued Fragmentation, Isolated Europe and Differentiated Global Action scenarios. In practice, it is expected that in the three scenarios with competitive disadvantages, part of the existing ammonia and cracker capacity will close and no new installations will be built to replace it. In the absence of any investments in new installations, production would gradually decline towards

 $^{^{54}}$ This estimate was obtained by multiplying the direct emissions for the Continued Fragmentation scenario as show in Figure 7-2 by the assumed differences in CO₂ costs for this scenario in Figure 6-2.

2050⁵⁵ and will be replaced by additional imports into Europe. As such, the production projections used in the Isolated Europe scenario for the chemical industry can by no means be regarded as a "worst of the worst" type of scenario, and also production in the Differentiated Global Action and Continued Fragmentation scenarios for the chemical industry could well be less, compared to the projections used in this Roadmap.

In the <u>Level Playing Field</u> scenario, converging energy and feedstock prices are assumed as well as an equal CO_2 price signal across the world. Under such a scenario, driven by increasing demand for chemical products, a fully integrated chemical value chain will remain within Europe and the European chemical industry continues to grow. Efficient highly integrated production sites and innovation further strengthen the competitive position of the European chemical industry in this scenario.

Zooming in on the five subsectors, the following pattern can be observed. For the subsector <u>Petrochemicals</u> the cost differential in energy, feedstock and CO₂ puts pressure on the competitiveness of this subsector in Europe. As a result, from 2020 onwards this subsector sees negative growth rates for the Isolated Europe scenario and the sector is also under pressure under the moderate CO₂ price differentials assumed in the Differentiated Global Action and Continued Fragmentation scenarios. The declining production in the consuming sectors in the isolated Europe scenario also has a negative impact on the demand for Petrochemicals.

In each of the scenarios, the production of <u>Basic Inorganics</u> grows largely in line with demand. Some of the Basic Inorganic products (e.g. chlorine, industrial gases) are difficult to transport and as a result, large net trade flows do not occur even though energy and CO_2 costs as a share of sales value are high. This is, however, not true for all products in this sector. Ammonia can, for example, be traded. A large share of the production of the Basic Inorganic industry is consumed by the chemical industry itself and the demand for Basic Inorganics is thus negatively influenced by the lower or even negative growth of these consuming industries in the isolated Europe scenario.

The <u>Specialty Chemicals</u> and <u>Consumer Chemicals</u> subsectors are less exposed to competitive disadvantages resulting from energy and CO_2 cost differences, because these costs per unit of sales are much lower. These sectors can benefit from a fully integrated value chain of chemical production in Europe and are thus negatively influenced by the negative outlook for the basic chemical industries. As a result, the very positive trade balance for these subsectors reduces to a more or less balanced trade situation in 2050 for the Isolated Europe scenario. In the Level Playing Field scenario these subsectors form the drivers of the relatively strong growth in the European chemical industry compared to the other scenarios.

⁵⁵ The fact that it is difficult to attract investments in production capacity for olefins and ammonia becomes apparent when looking at investments in recent years. The last significant investments in new ammonia and cracker products production were before 2000.

In the <u>Polymers</u> subsector the bulk polymers grow in line with the Petrochemical subsectors, while the engineered polymers develop more in line with the Specialty Chemicals subsectors.

7.3 The role of energy-efficient and low carbon technologies

7.3.1 Feedstock

Bio-based chemicals

Future shares of bio-based feedstock are based on an analysis of the ratio between fossil prices and biomass prices and on a high-level analysis of development of key drivers, like innovation and the need for new production capacity. Methodologically, all additional bio-based production has been taken into account as new installations. For the Isolated Europe scenario, this limits the increase in the share of bio-based feedstock⁵⁶.

As discussed in Section 5.2.1, a large share of currently produced chemicals can in principle be made from bio-based feedstock. From an economic and energy point of view, the bio-based route is currently only for a limited share of the chemicals produced the preferred choice. All scenarios show a clear trend towards an increasing use of bio-based feedstock, chiefly in the Specialty Chemicals and Consumer Chemicals subsectors. Driving forces for this increase are the further development of biobased routes and, for the Continued Fragmentation and Isolated Europe scenarios, the increase in oil price relative to the biomass price. For the Differentiated Action and Level Playing Field scenarios, development and use of bio-based routes is expected to be quicker, to which the CO₂ price signal to all use of fossil fuels contributes. In the Isolated Europe scenario, development and use of bio-based routes is lower, due to the less innovative climate. In this Roadmap, regional potentials within Europe have not been further studied (Box 7-1).

⁵⁶ In reality, bio-based processes are also developed that can replace fossil-feed based processes in existing equipment. This would – for the Isolated Europe – lead to a higher use of bio-based feed, and could – for all scenarios – have an impact on the energy consumption and the fuel mix.

Box 7-1 Potential for bio-feedstock is region specific

The regional workshops (Section 1.4) made clear that the use of biomass as feedstock gets significant attention in several EU Member States. Representatives from Germany, and France indicated that already substantial amounts (~10%) of biomass are used as feedstock and France reported a voluntary target of 15% biomass feedstock towards 2020. In Northern Europe, significant R&D efforts are ongoing regarding the use of forestry residues and other forestry products as feedstock for the chemical industry. Northern Europe could play an important role in the further development of a bio-based chemical industry. These examples show that there are significant regional differences regarding the potential and applicability of biomass as feedstock.

Future shares of bio-based feedstock for the products studied in detail showed that:

- Bio-based production of ammonia is very limited, due to high associated investment costs;
- Bio-based production of cracker products becomes an interesting option in the decarbonisation scenarios between 2030 and 2050. (Imported) bio-ethanol⁵⁷, or lignocellulosic-based ethanol could be sources for this route and are assumed to gain markets share between 2030 and 2050 in the Level Playing Field and Differentiated Global Action scenarios.

The resulting use of bio-based feedstock⁵⁸ is given in Figure $7-11^{59}$.

⁵⁷ Reference is made to Section 6.4 for more information on the pricing of ethanol.

⁵⁸ Bio-based feedstock is defined as the amount of biomass equal the caloric value of the product by analogy with how feedstock use in ammonia and cracker products production is defined

⁵⁹ Due to uncertainty in the current share of bio-feedstock and the allocation of this feedstock use to individual subsectors, the biomass feedstock uses should be regarded as estimates only.



Figure 7-11 Feedstock use in the four scenarios. Differences in total feedstock use result from differences in total production

Figure 7-11 shows absolute feed use. Therefore, differences in production levels are an important factor in these graphs. Reduced European production leads to more import of chemicals / other goods. The level of GHG emissions reduction achieved in Europe would, in case of increasing imports, be achieved at the expense of increased emissions elsewhere. This would happen with no overall reduction in global GHG emissions or even a potential increase as explained above. In Box 7-2, the total biomass feedstock and fuel use (discussed in Section 7.3.3) is put into the perspective of overall biomass availability.

Box 7-2 Is there sufficient biomass for the production of bio-based chemicals?

The **Level Playing Field** scenario in 2050 requires mostly the biomass feedstock and fuel use, **2,273 PJ (=2.3 EJ)**. This number reflects the amount of biomass ending up in a product, and biomass use for energy purposes⁶⁰.

The total global biomass available for energy is huge, the highest estimates exceeding 1000 EJ per year (Smeets, 2008). However, when constraints related to biodiversity protection, water limitation, and soil degradation are taken into account, an IPCC (2011) assessment estimates that a global technical potential of 500 EJ is available in 2050, including all kinds of residues, surplus forestry, surplus on good land, production on marginal and degraded land, taking into account plant productivity improvement. In most global low carbon scenarios the utilisation of bio-energy is in the range of 75–200 EJ (The Ecofys Energy Scenario in Ecofys-WWF (2011); IPCC, 2007; Vuuren, 2007; Greenpeace, 2010; Shell, 2013).

In the EU, the availability of sustainable biomass is much more limited. Two key materials to produce bio-based materials which are available in Europe are straw and forestry products. These two together form a large part of the EU potential of biomass suitable for production of bio-based chemicals.

Forestry products today provide 2800 PJ of primary energy per year in EU (ECF, 2010); by increasing the capture of forest residue an additional 600 PJ of forestry products could become available in 2020 (ECF, 2010).

Monforti et al. (2013) gives a range between 800 PJ and 2,100 PJ for the potential of straw in the EU from different literature sources. Sustainability criteria were not applied to all sources. The potential of straw that can *sustainably* be made available is still subject to further research.

Compared to estimates of global utilisation of bioenergy of 750–200 EJ per year, 2.3 EJ for bio-based chemicals and bio energy seems feasible. Within Europe, there would be sufficient feedstock available from either woody biomass or straw if the upper ends of the potential supply estimates are achieved. However, the availability of feedstock will depend on demand from competing uses of biomass, notably for energy, and on further research to ensure sustainable levels of feedstock harvesting.

⁶⁰ Feedstock use defined on the basis of the calorific value of the products in line with cracker products and ammonia production. Biomass not ending up in the product also results in a higher number. This would require an assumption on an average yield from biomass to chemical products.

Valorisation of plastic waste: Recycling

Recycled polymers can contribute to the feedstock requirement of the chemical industry via three main routes: mechanical recycling, back-to-monomer, and back-to-feedstock (see Chapter 5).

Mechanical recycled plastics can substitute primary polymers to a limited extent, constrained by the quality of the recycled material and the high quality demands for most polymers. Nevertheless, the use of mechanically recycled plastics increases in all scenarios, due to technological developments and the increase in the combined price of oil and CO_2 pricing on feedstock in the decarbonisation scenarios from 2030 onwards. The highest share of additional mechanical recycling is foreseen in the Differentiated Global Action scenario, where, compared to 2010, an additional 7% of Polymer demand is filled in by mechanically recycled polymers in 2050. This is taken into account by reducing EU production of Polymers by, in this case, 7%. In all other scenarios and years, substitution is less.

Back-to-monomer techniques will only become relevant for some high-value low-volume specialty products. The effect on the energy demand of the chemical industry up to 2050 is expected to be limited and is not further taken into account.

Remaining plastic waste can either be used in "back to feedstock" routes (to produce for example olefins) or be used to recover energy. The attractiveness of the "back-to-feedstock" routes depends partly on the dynamics of the future waste markets. Under the assumptions made in this Roadmap, only a limited role for this route is assumed for the production of cracker products. But, there might be upward potential, depending on how this option develops in comparison with other waste conversion technology such as energy recovery. Continued landfilling is not assumed.

ССИ

The reduction of use of fossil or bio-feedstock by new processes using CO_2 as feedstock has not been quantitatively included in the tool, as developments are still in their infancy. R&D efforts are ongoing, finding new ways to use CO_2 as feedstock, and commercialise these. A scoping study on the utilisation of CO_2 as a renewable resource was initiated jointly by Cefic and EuCheMS in 2012. Many activities related to CO_2 utilisation as feedstock have already been initiated at national, regional and company level in and outside Europe. The objective of the joint Cefic-EuCheMS initiative is to create by the end of 2013 a European research and innovation roadmap that would address the utilisation of CO_2 for the production of basic chemicals, fine chemicals, Polymers, fuels and power to gas considering different pathways including the photochemical conversion of CO_2 to biomass (see also Box 5-3).

Any effect of these research efforts would enlarge the reduction of the fossil share of feedstock shown in Figure 7-11, potentially at the expense of an increase in the energy use.

7.3.2 Improve energy efficiency of process

Subsectors

The development of energy efficiency is impacted by several factors:

- The scenario dependent development of the efficiency of stock already operating in 2010.
- Scenario dependent improvement rate of the energy efficiency of new plants.
- The development of European production. A higher growth results in more significant energy efficiency improvements, due to the higher share of new stock that is typically more efficient.
- The replacement of existing stock by new stock that is typically more efficient (see Section 6.5 for more details).
- The implementation level of CCS (due to the associated energy consumption).

For the five subsectors, the development of energy efficiency has been determined using the generic approach as outlined in Section 5.3.2. The efficiency potentials shown in Figure 5-5 to Figure 5-8 are multiplied by 80% for the Continued Fragmentation scenario, 90% for the Isolated Europe scenario, 120% for the Differentiated Action scenario, and 110% for the Level Playing Field scenario based on the energy and CO_2 price projections and the assumed speed of innovation as outlined in Chapter 6. Similar scenario dependence was assumed for the energy intensity of new plants in these subsectors, and for the new plants for the products studied individually. The relatively low rate for the Isolated Europe scenario (with similar energy price and CO_2 prices), reflects that only if industry has the confidence to invest in Europe will large energy efficiency improvements be made. The resulting energy efficiency improvements for the five subsectors, as well as those for the products studied in more individual detail, are given Annex 3.

When interpreting the results, it should be taken into account that:

- The generic improvement factors are not based on individual products assessments and treat all different products in a subsector as equal, whereas in reality a subsector covers many different products.
- The generic improvement factors for subsectors "Other Petrochemicals" and "Other Basic Inorganics" do not include the products assessed separately (cracker products, ammonia, chlorine, nitric acid), as this would lead to double counting.
- The underlying information is stronger for subsectors "Other Petrochemicals", "Other Basic Inorganics" and "Polymers" than for the subsectors "Consumer Chemicals" and "Specialty Chemicals", which are even more diverse and which have not been the primary focus of this Roadmap.
- All new stock built in a given period is assumed to have the energy efficiency of new stock at the end of that period (so for example all new stock built between 2020 and 2030 is assumed to have the characteristics of new stock in 2030). This leads to an underestimation of energy use for these installations.

- The energy efficiency potentials for the subsectors are by no means intended as representing autonomous developments and—especially for the subsectors Specialty Chemicals and Consumer Chemicals—require significant innovation and deployment of the resulting new technologies. The potentials identified cannot be used to derive annual improvement rates. Improvement can well be much lower in some of the years, until the introduction of a game changer causes a big step again.
- For subsectors Specialty Chemicals and Consumer Chemicals, the contribution of the effect from process intensification and other process improvements dominate the technical improvement potential. While according to the European Roadmap for process intensification (Creative Energy, 2007) and SPIRE (2012) Process Intensification offers most potential for complex and multi-step reactions, the extrapolation of this number to both subsectors is approximate. Furthermore, it is likely that some of this potential lies in an improvement of selectivity and would, therefore, only partly lead to a reduction of energy use in the respective sectors, and partly to a decrease in use of raw materials from Petrochemicals and Basic Inorganics; in this Roadmap, this split has not been taken into account, and all effects have been attributed to energy efficiency improvements in the two subsectors.

Figure 7-12 summarises the development of the energy intensity for the average stock (in energy use per \in million sales). Energy efficiency improves in all scenarios, quickest in the Differentiated Global Action scenario. For Other Petrochemicals, Other Basic Inorganics and Polymers, it improves least in the Isolated Europe scenario (due to the lowest share of new stock in combination with the assumed improvement rate for existing plants). Stock turnover is assumed to be quicker for Specialty Chemicals and Consumer Chemicals, with the consequence that all plants in 2050 are assumed to be new plants. Therefore, the lowest energy efficiency improvement would take place in the Continued Fragmentation scenario, due to the lowest innovation rate and the lower incentives resulting from energy and CO₂ prices.



Figure 7-12 Range of energy (fuel and electricity) intensity for the production of generic subsectors for the scenarios studied, 2010–2050⁶¹

Ammonia

For **ammonia**, the energy efficiency of stock operating in 2010 can on average in all scenarios be improved cost effectively by approximately 20%, by large and moderate improvements of the reformer section, synthesis and CO_2 removal, and by improved process control, process integration and motors. For all scenarios, it is assumed that these measures are, so far as possible applied in 2030. The other measures described in Chapter 5 are not cost effective as confirmed in the topic team Technology and Innovation and by a technology provider.

The energy efficiency of new plants (baseline based on Steam Methane Reforming⁶²) is expected to improve significantly in the period up to 2050. Under the conditions assumed in this Roadmap, steam

⁶¹ The impact of bio-based feed is not included in this figure. The use of bio-based feed leads to a shift in energy use between the subsectors, which would make the interpretation of the graphs difficult.

methane reforming remains the dominant technology to produce ammonia in all scenarios, in some of the scenarios combined with CCS (Section 7.3.4).

Figure 7-13 represents the scenario-extremes for the development of the energy intensity of ammonia of existing plus new stock. For ammonia, the energy intensity develops best in the Level Playing Field scenario, as in this scenario the share of new stock is highest. The energy intensity improvement in the Isolated Europe scenario is lowest, as the share of new and thus improved plants is lowest, due to the limited investments in(more energy efficient)ammonia plants in that scenario.

Production projections were made for the subsector Basic Inorganics as a whole, not specifically for ammonia. Production projections for ammonia are thus assumed to be identical to those of the subsector Basic Inorganics. In practice, see also Section 7.2, it is expected that in the Continued Fragmentation, Isolated Europe, and Differentiated Global Action scenarios, part of the existing ammonia capacity will close and that no new installations will be built to replace it. In the absence of any investments in new installations, production would gradually decline towards 2050. This would lead to a development of the energy intensity as described in Section 5.6 for stock operating in 2010, which is also shown in Figure 7-13, hence to a much lower decrease in energy intensity.



Figure 7-13 Range of energy (fuel and electricity, excluding feedstock) intensity for the production of ammonia for the scenarios studied, 2010–2050 and range of energy intensity for stock operating in 2010

⁶² Development of this technology is assumed to be scenario specific, by multiplying the reduction in energy use relative to 2020 (as listed in Section 5.6) with 80%, 90%, 120% and 110% for Continued Fragmentation, Isolated Europe, Differentiated Global Action and Level Playing Field respectively.

Cracker products

The improvement rate for stock operating in 2010 will be the result of a mix of measures as described in Chapter 5. The feasibility of applying different measures is to a large extent determined by the steam balance of the cracker and its vicinity. Deviating from the approach for the other individually assessed products, the measures were not individually assessed on the basis of investment decisions for each measure. This is due to data availability issues and because often measures would lead to the same effect with the risk of double counting. Therefore, using the knowledge available on the measures and taking the risk of double counting and the shape of the benchmark curve into account, the total effect of the measures in the different scenarios was established for each scenario and period. This was agreed on with the topic team Technology and Innovation. The description on this subject in Chapter 5 gives a good flavour of the measures that are expected to deliver the efficiency improvement.

In the Continued Fragmentation scenario, the energy efficiency of stock operating in 2010 is expected to improve by 14% (2030) and by 23% (2050) compared to 2010. In the Differentiated Global Action scenario, these numbers are 21% (2030) and 34% (2050). Improvement rates for the other scenarios are in between, in line with the scenario dependence used for the subsectors as explained above. Key factors include fossil fuel prices, CO_2 costs and innovation rates.

It is important to note that:

- The potential of the measures is based on literature input, reviewed in the topic team Technology and Innovation.
- Some of the measures have already been taken in some of the crackers (partly) explaining the differences as shown in the benchmark curve (Ecofys et al., 2009). However, not all measures can be applied to each of the crackers.
- Some of the measures with significant effect still require significant innovation and to reach "proven technology" status before they can be implemented; for part of these, the economic attractiveness as a retrofit option has not been investigated in detail.
- Furthermore, once again, the steam balance of the cracker and its vicinity is a key factor in the feasibility of many measures. The given numbers cannot, therefore, be applied to all crackers.

New stock:

The baseline technology for new cracker products stock is an improved traditional cracker (or catalytic cracking, refer to Section 5.6.2). This technology is assumed to develop further in time⁶³,

⁶³ Development of this technology is assumed to be scenario specific, by multiplying the reduction in energy use relative to 2020 (as listed in Section 5.6) by 80%, 90%, 120% and 110% for Continued Fragmentation, Isolated Europe, Differentiated Global Action and Level Playing Field respectively.

and is expected to be combined with CCS to a significant extent after 2030 in the Isolated Europe, Differentiated Global Action and Level Playing Field scenarios. As stated in Section 7.3.1, (imported) bio-ethanol⁶⁴, or lignocellulosic-based ethanol could be sources for this route and are assumed to gain markets share between 2030 and 2050 in the Level Playing Field and Differentiated Global Action scenarios. The back to feedstock recycling option is implemented very limitedly after 2030⁶⁵ (refer to Section 7.3.1).

Natural gas to methanol, followed by methanol to olefins, is not economic at the gas prices in the scenarios due to the relatively high amount of gas needed.

Figure 7-14 gives the range of the development of the energy intensity of cracker products for the scenarios. The energy intensity develops best in the Level Playing Field scenario, due to the highest share of new stock, and due to the implementation of the ethanol-to-ethylene route, which has a relatively low energy demand⁶⁶. The energy intensity improvement in the Isolated Europe scenario is lowest, as the share of new and thus improved plants is lowest. When interpreting this graph, it should be taken into account that the endothermicity for the naphtha based route is 5 GJ per tonne cracker products, which means the energy efficiency improvements for production of cracker products is significant.

Production projections were made for the subsector Petrochemicals as a whole, not specifically for cracker products. Production projections for cracker products are thus assumed to be identical to those of the subsector Petrochemicals. In practice, see also Section 7.2, it is expected that in the Continued Fragmentation, Isolated Europe, and Differentiated Global Action scenarios, part of the existing cracker capacity will close and that no new installations will be built to replace it. In the absence of any investments in new installations, production would gradually decline towards 2050. This would lead to a development of the energy intensity as described in Section 5.6 for stock operating in 2010, which is also shown in Figure 7-14, hence to a much lower decrease in energy intensity.

⁶⁴ Reference is made to Section 6.4 for more information on the pricing of ethanol.

⁶⁵ Only in the Differentiated Global Action scenario and only a couple of percent of newly built stock in that period.

⁶⁶ Energy use would have been higher if also the production of ethanol from biomass had been included. This energy use now still takes place, but is assumed to take place outside the European Chemical Industry. This only affects the lower line of the graph in 2050.



Figure 7-14 Range of energy (fuel and electricity) intensity for the production of cracker products for the scenarios studied, 2010–2050 and range of energy intensity for stock operating in 2010

Chlorine

Chlorine plants operating in 2010 based on mercury cell technology will be converted to membrane based technology. This reduces electricity consumption significantly, but at the expense of steam consumption to concentrate caustic soda to market specification.

The biggest impact on the energy use of chlorine plants is however the retrofit to oxygen-depolarised cathodes (ODC) technology. Its economics depend, among other things, on the need to replace the coproduced hydrogen and on the future improvement of ODC technology.

Ten per cent of membrane plants have monopolar cells; the others are based on bipolar cells, which is somewhat more energy efficient. Upgrading the monopolar cells to bipolar cells will become more profitable with increasing industrial electricity prices; however, on-going developments for monopolar cells could achieve the same effect for the smaller plants.

There is no compelling reason for diaphragm operators operating in 2010 to switch to membrane cells. Power consumption differences are minimal (input provided by the topic team Technology and Innovation). The membrane process is, in close cooperation with the topic team Technology and Innovation, taken as the baseline technology for the future⁶⁷, with limited improvements of the energy efficiency. If future market specifications allowed lower concentrated caustic soda, diaphragm based chlorine production could be an option as well with comparable energy consumption. This is not taken into account further (European Commission, 2011c). ODC could again become an interesting variant for the membrane cell based baseline, depending on its future development and the need to replace coproduced hydrogen. In this Roadmap, an optimistic assumption on the implementation of ODC has been taken. Should ODC not be implemented, the increase in energy use as shown in Figure 7-15 is limited.

Figure 7-15 represents the scenario-extremes for the development of the energy intensity of chlorine. The energy intensity develops best in the Level Playing Field scenario, due to the largest share of new, thus improved plants, while the opposite occurs for the Isolated Europe scenario.



Figure 7-15 Range of energy (fuel and electricity) intensity for the production of chlorine for the scenarios studied, 2010–2050

7.3.3 Heat source changes, renewables and CHP

For cracker products, ammonia and chlorine production, the heat sources of current and future technologies is defined by the technologies applied. For the subsectors studied in general, the heat sources for the 2010, 2020, 2030 and 2050 time slots given in Figure 7-16 are applied to all subsectors. The numerical values included in this Figure are given in Annex 3.

⁶⁷ Development of this technology is assumed to be scenario specific, by multiplying the reduction in energy use relative to 2020 (as listed in Section 5.6) by 80%, 90%, 120% and 110% for Continued Fragmentation, Isolated Europe, Differentiated Global Action and Level Playing Field respectively.



Figure 7-16 Heat sources assumed for the four scenarios

Over time, a gradual phase out towards 2030 is assumed for the current 10% share of coal use in the chemical industry, driven by environmental concerns related to the use of coal and by the upward pressure from CO₂ prices for all scenarios. For all scenarios, a share of 5% oil products in the fuel share is assumed for 2030 and 2050 to account for residual fuel oil use resulting from incomplete conversions in the Petrochemical industry. Driven by upward pressure on fossil fuel prices, the use of geothermal heat becomes more profitable over time. The feasibility of using geothermal heat in the chemical industry is, however, limited in terms of temperature levels that can be reached (up to 250 °C), combined with the situation of an overall excess of low temperature heat in the chemical industry resulting from heat integrated sites with an overall high temperature heat demand. Nevertheless, geothermal heat could be an option for smaller non-integrated sites with a demand for low temperature heat, and geothermal heat is assumed to have a share in the heat sources up to 4% in 2030 and up to 10% (differentiated global action scenario) in 2050. Over time, the use of biomass becomes profitable as compared to fossil fuels, due to the upward trend in the prices of fossil fuels in combination with the CO_2 prices. Only after 2030, this results in a significant uptake of biomass as fuel (share in the heat sources in 2030 assumed to be at most 5%). But in this later time period, biomass competes with the use of fossil fuels in combination with carbon capture and storage, and with other biomass applications, resulting in a maximum share of 20% in 2050 for the Differentiated Global Action scenario.

In this Roadmap, no detailed projections on the future of CHP installations in the chemical industry are developed. The future of CHP is obviously very much linked to the development of the electricity market in Europe in the decades to come. Over time, the large share of renewables in the power mix potentially results in lower load factors of fossil power production, posing a risk to the profitability of fossil power generation in general and that of industrial CHP installations serving a heat demand for continuous processes more specifically (e.g. the need for back-up heat facilities etc.). Furthermore, over time, fossil fuelled CHP will have higher carbon intensity per unit of power as compared to centralised power production using large shares of renewables and power plants with CCS. This implies that to further decarbonise, CHP would be used in biomass application and / or in combination with carbon capture and storage. Despite these negative developments, the EU Energy Roadmap (European Commission, 2011b) foresees a significant increase in heat consumption from CHP for the total European industry with a factor 3–5, driven by support policies resulting from the application of the Energy Efficiency Directive (European Commission, 2012d) and by carbon pricing (European Commission, 2011b, pp. 134-135).

For the projections, the heat sources as given above are applied for meeting the heat demand of the chemical industry, without a specification on the share of this heat that results from CHP. Emission factors for electricity derived from the EU Energy Roadmap are applied taking into account the overall (i.e. including CHP) electricity mix assumed in the two scenarios that form the basis for the industry electricity cost projections. It is important to carefully consider the future of CHP for industry in the discussion on the decarbonisation of the power supply in Europe, given the potential CHP has on energy efficient technology for the production of heat and electricity.

7.3.4 Emission abatement

CCS

To determine the economic attractiveness of CCS, its main cost drivers (available technology, plant size, energy costs, availability of existing transportation and / or storage facilities) have been considered. Besides these key drivers for CCS, a clear learning effect for capturing and compressing and, to a smaller extent, for transporting CO_2 is also foreseen. The share of energy in the total CO_2 abatement costs is significant, with only limited scenario dependence. Considering the specific products identified, CCS can be applied to process emissions (in the case of ammonia as well as to combustion emissions (ammonia, cracker products and other subsectors).

The application of CCS to combustion sources has been determined based on the cost assumptions given in Figure 5-10 and Figure 5-11. Until 2030, assumed CO_2 prices do not yield economically attractive abatement of CO_2 via CCS to combustion sources, so that no CCS to combustion sources is assumed until 2030. By 2050, in all decarbonisation scenarios, CCS to combustion sources is attractive for all subsectors.

It should be noted that several barriers exist to implementing CCS on a large scale:

- The costs of CCS as given in this Roadmap are uncertain. They will only become reality if CCS is applied on a large scale for many sectors and sources of CO₂. It remains to be seen who would be willing to make the first large initial investment in infrastructure and storage facilities. Especially for smaller, dispersed emissions sources, it therefore remains questionable whether CCS will easily become feasible and cost-effective.
- Some sites have site specific limitations towards the use of CCS such as the distance to storage locations, lack of physical space on site to install capture technology etc.
- There are, for many EU Member States, many public acceptance and legal issues to be overcome (Box 7-2).
- Related to this, the additional energy use that CCS involves remains a drawback that is likely to continue to play a role in the public debate about CCS.

Provided that most of these barriers could ultimately be overcome towards 2050, it is assumed that 90% (for Other Petrochemicals, Other Basic Inorganics, Polymers, ammonia and cracker products) and 75% (for Specialty Chemicals and Consumer Chemicals) of emissions from fossil fuels could in principle be captured and stored, taking into account technical limitations related to plant size etc. For Isolated Europe in particular, this is a rather positive assumption, because the use of CCS will, for this scenario, result in significant additional costs as compared to competing producers outside Europe.

Box 7-3 Legal barriers for CCS in various countries

The lack of public acceptance and existence of legal barriers to CCS became apparent at the regional workshops. In several countries (e.g. Finland, the Netherlands), CCS pilots were stopped and other countries (e.g. Austria, Germany, France) have legislation in place that makes the use of CCS impossible. For the majority of EU Member States public acceptance is reportedly very low (not in my backyard) and the expectation was given that CCS is unlikely to play a significant role in the near future.

Nitric acid

In Chapter 5, it was already shown that for the case of nitric acid production, all plants are expected to have installed abatement technology with an average emission of 90% below the 2010 level. In

general, these measures are cost-effective and their implementation does not depend on the scenarios. In Figure 7-17 the results for the N_2O emissions intensity are given.



Figure 7-17 Decrease of N₂O emissions intensity for the different scenarios. Values apply to all 4 scenarios

The very small difference observed between the scenarios is due to shares of stock operating in 2010 and new stock not being the same in all scenarios.

7.3.5 Sensitivity Analysis

The results presented so far have been based on the set of energy prices for the different scenarios. Based on the economic attractiveness of measures or new technologies (compared to baseline technologies and each other) or with a more generic approach, the scenarios define a pathway towards 2050. To get a feeling for its dependence on energy prices, the impact of changing these has been assessed qualitatively:

- In the Isolated Europe, Differentiated Global Action and Level Playing Field scenarios, the main driver is the CO₂ price. Hence a higher price for *oil* or *gas* shows little differences in terms of penetration of measures and technologies for the products.
- For future ammonia and cracker products production from bio-based materials, dependence between biomass (in particular ethanol) prices and the oil price will be an important driver.
- For the future fuel use, the renewable share at current scenario prices is at most one third (either biomass or geothermal heat) and the remainder will be provided mainly by burning natural gas. This means that especially a higher gas price (including policy costs) will increase the share of renewables in the future heat sources.

- For a power price 50% higher than assumed, ODC technology for chlorine production (both retrofit and new installations) becomes more attractive by 2050. Furthermore, with this 50% higher price, it is economically viable to build a chlorine plant with overcapacity and to produce only in times of very cheap or free (renewable) electricity, provided this free electricity is available for a significant amount of hours per year.
- At a 50% lower power price it becomes attractive to apply electrolysis routes to produce ammonia (either high- or low-temperature electrolysis or solid state synthesis). Such a possible power price advantage could potentially not be expressed through the normal market price, but through cost remuneration from a kind of capacity mechanism. Such a mechanism would cope with intermittent renewable energy sources.
- Also, this 50% lower power price would be favourable for CCU, as this reduces the cost of energy required to build a new carbon framework. Of course, this still only serves a point in case generation of this electricity does not lead to CO₂ emissions, but is generated from renewable sources.
- The effect of the power price on CCS is limited, due to relatively low share of power in the total operational costs. This means that implementation of CCS is relatively insensitive to differences in the industrial electricity price.
- To get an impression of the impact of differences in the CO₂ price, a comparison between the Differentiated Global Action scenario and the Continued Fragmentation scenario gives some insight. As other factors, such as production development, play a role as well, this would just be indicative.

Above, only effects on energy and GHG efficiencies are discussed. Some of the variations would also impact competitiveness of the European chemical industry, and thereby the trade ratio. Reduced European production leads to more import of chemicals / other goods, and hence to the import of emissions.

8 Results – Enabling Europe's low carbon development

8.1 Current and emerging enabling technologies

The innovative solutions of the chemical industry contribute to energy efficiency improvements and avoided GHG emissions in all sectors of the economy. At present, the European chemical industry delivers an essential contribution to low carbon technology solutions, which avoid 1,500 Mt CO₂ equivalents of emissions as compared to respective alternative technologies still in use (Chapter 4). Current chemical applications with an enabling effect will continue to contribute to avoided emissions and energy efficiency improvements in the future. In addition, emerging solutions using chemical products will emerge. Table 8-1 gives an overview of current and emerging chemical applications that contribute to energy efficiency and avoided emissions.

	Group 1: Improved energy-efficiency and direct avoided emissions	Group 2: Increased renewable energy generation
Current chemical applications (2010)	 Insulation (EPS, XPS, PU)* Lighting (Compact Fluorescent Lamps)* Marine antifouling coatings* Light-weighted automotive parts* Packaging* Fertiliser and crop protection* Low temperature detergents Diesel and gasoline additives Synthetic lubricants Green tyres 	 Wind power* Solar power*
Emerging chemical applications (2010–2050)	 Insulation (aerogels, vacuum insulated panels) Lighting (LED and OLED) Smart windows (incl. thermochromic roofing) Energy-efficient water treatment High performance packaging materials Conductive polymers for printable electronics 	 Polymer electrolyte fuel cells (PEFC) in electric cars Advanced solar cells

Table 8-1Current and emerging chemical applications contributing to energy efficiency
improvements and avoided emissions

 * Chemical applications of which the avoided emissions have been quantified in Chapter 4.
The source used for current chemical applications in Table 8-1 is ICCA (2009). The sources for emerging chemical applications are ICCA (2012), SPIRE roadmap (SPIRE, 2012), Building Up roadmap (Building Up, 2012), SusChem Hybrid Workshop (SusChem, 2010), EuCheMS (2011), Carbon Trust (2012) and the Dutch Chemical Roadmap (VNCI, 2012).

Emerging chemical applications can become the next generation of enabling products when they are truly competitive in the market in terms of performance and production costs. Accordingly, emerging technologies that are currently commercially available on a small scale, such as vacuum insulated panels, LED, and advanced solar cells, may considerably contribute to the energy and emissions savings in the period up to 2050. Due to the uncertainty of the (speed of) future uptake of emerging chemical applications and the development and breakthrough of completely new technologies, it is challenging to make an educated estimate on the total amount of avoided emissions in 2050. The emerging chemical applications given in Table 8-1 are in different stages of development (Table 8-2) and are briefly discussed in Box 8-1.

Technology	R&D	Pilot	Proven technology
Aerogels			
Vacuum insulated panels			
Smart windows and roofing			
LED			
OLED			
Energy-efficient water treatment			
Conductive polymers for printable electronics			
Polymer electrolyte fuel cells (PEFC) in electric cars			
Advanced solar cells			
Advanced batteries			
High-Temperature Superconductors			
High performance packaging materials			

 Table 8-2
 Development status of emerging chemically derived low carbon technologies

Box 8-1Some examples of emerging technologies contributing to energy
efficiency improvements and avoided emissions during use

Insulation – aerogels and vacuum insulated panels

Improved insulation materials, such as aerogels and vacuum insulated panels (VIPs) have a lower thermal conductivity compared to conventional insulation materials. Aerogel is a very light porous material with a very low density and thermal conductivity. Aerogel is created by replacing the liquid component of a gel by a gas. VIPs contain gas-tight compartments from which the air has been removed and have a very low thermal conductivity. The inside of these compartments consists of support materials, for example glass fibre, fumed silica or aerogels and contains chemicals to collect gases which leaked through the membranes.

Aerogels as well as VIPs are not fully developed yet. Aerogels are used for specialty applications in industry and are commercially available on a small scale. Fragility of the material and high costs need to be addressed in order to make widespread commercial application for insulation purposes possible (ICCA, 2012; Open Source Nanotech Initiative, 2013).

Smart windows and roofing

Electrochromic, thermochromic and photochromic glazing consists of glass that changes colour and opacity in response to respectively electricity, temperature and light. This glazing can be used in windows and roofing to reduce the heating and cooling demand of buildings. During warm periods, the transmission of solar heat can be limited, whereas during cool periods the transmission of solar heat is unaffected. This can reduce the need for air conditioning and lead to savings in energy and CO₂. Currently, photochromic glazing is still in an R&D stage and thermochromic and electrochromic glazing is in a demonstration stage. Using these techniques for roofing purposes requires improvements such as long term resistance to dirt and microbial growth. For windows, the high price, durability issues and cosmetic issues act as barriers to wide scale introduction (ICCA, 2012).

Box 8-1 Some examples of emerging technologies contributing to energy efficiency improvements and avoided emissions during use (continued)

Lighting (LED and OLED)

Light emitting diodes (LEDs) and organic light emitting diodes (OLEDs) are a type of solid state lighting containing semiconducting materials. LEDs and OLEDs have an improved efficiency and lifetime compared to conventional lighting sources. An increased use of LEDs and OLEDs in the future can lead to energy efficiency improvements and hence avoided CO₂ emissions. LEDs exist already for some time, but the recent development of white LEDs has led to additional applications. Some types of OLEDs are already used in display technologies. Other applications of OLEDs, such as flexible and curved displays are still under development. Research is being conducted on reducing the sensitivity of LEDs to high temperature. This will make a broader application possible and increase efficiency even further, by eliminating the need for cooling. The use of rare earth materials in LEDs can become a bottleneck for large scale application of LEDs, because these materials are scarce and can be toxic. OLEDs are a newer technology and improvements in costs and light output would facilitate large scale application. In addition, the lifetime of the OLED in practice is still uncertain (SPIRE, 2012; SusChem, 2010; Edison Tech Center, 2010).

Energy efficient water treatment

The European chemical industry can contribute to energy efficiency improvements and avoided emissions in water treatment by optimising the porosity of membranes, reducing membrane fouling, reducing the need for and optimising pre-treatment and improving the lifetime of the membranes. One example is reverse osmosis, a membrane based desalination technology. Reverse osmosis works by applying pressure to one side of a membrane which filters out large molecules and allows pure solvent to pass to the other side. This process requires a lot of electricity. Chemical innovations can improve the energy-efficiency of this process.

Conductive polymers for printable electronics

Conductive polymers are organic polymers which are capable of conducting electricity. Conductive polymers are easy to process and can be a low-energy / resource technology for simple electronic devices. A lower consumption of energy and resources by the use of conductive polymers can lead to reduced CO_2 emissions. The application of conductive polymers is currently in the pilot stage. Solving problems related to instability under normal atmospheric conditions, improving the consistency, dispersability and solubility of the material and an overall improvement of synthesis techniques can reduce production costs and free the way for widespread application (NanoMarkets, 2011; Strong and Lunt, 2001).

Box 8-1 Some examples of emerging technologies contributing to energy efficiency improvements and avoided emissions during use (continued)

Polymer electrolyte fuel cells (PEFC) in electric cars

Fuel cells will be essential for the efficient use of hydrogen in transport. PEFCs are able to operate at lower temperatures and are smaller and lighter than other fuel cells. Breakthroughs in the production process of PEFCs can make fuel cell electric vehicles cost competitive with combustion engine vehicles. This increases the introduction rate of fuel cell cars on the market. Since fuel cell electric vehicles emit less CO_2 per kilometre than combustion engine vehicles, this will lead to the avoidance of large amounts of CO_2 (Carbon Trust, 2012). The concept of a fuel cell has been around for a long time, but the use of PEFC in electric cars is relatively novel and currently in the pilot stage. The Carbon Trust presents three developments that could lower the production costs and facilitate large scale deployment: zero-platinum liquid catalyst, high power density membrane and novel stackable board architecture.

Advanced solar cells

Advanced designs of solar cells, which include organic photovoltaics, high-efficiency compound semiconductors and ultra-high-efficiency thin-film solar cells, can increase solar power penetration due to their advantageous economics. This increased deployment of solar energy will decrease the need for fossil fuelled electricity production and reduce CO₂ emissions. (ICCA, 2009). Advanced solar cells consist of different technologies, some of which are still in the R&D stage and some are already in a pilot or commercial stage. Barriers to advanced design solar cells containing rare earth materials are the costs associated with the use of these materials.

Batteries for Mobility and Stationary Storage

As energy storage of the future, batteries are a key technology for a climate friendly energy supply. While the existing first and second generations of lithium-ion batteries are already being used in laptops, smartphones and cameras, newer and more stable systems have to be developed for the third and fourth generation. Key factors for the success of the new batteries are high effectiveness, high safety and an affordable price (EuCheMS, 2011; SPIRE, 2012). Today's electrically powered vehicles have a limited operating range, despite lightweight construction. The goal in developing high performance battery systems is to at least triple the operating range in the next five years. Stationary storage will serve an important buffer function in balancing supply and demand for electricity from regenerative energy sources. Because capacities of the existing systems are too low or their use is not economical, electrochemical and chemical storage systems are designed to take up excess energy—generated in strong sunlight or wind conditions but not needed—and deliver it again later as required.

Box 8-1 Some examples of emerging technologies contributing to energy efficiency improvements and avoided emissions during use (continued)

High Temperature Superconductors

The application of High Temperature Superconductors (HTS) will play an integral part in the future extension of the grids. Conventional equipment, such as cables, transformers and generators, can be extended more efficiently and compactly, because HTS make a ten-fold to more than one hundred-fold higher power density possible compared to conventional conductors like copper and aluminium. In recent years, industrial applications of HTS technology have also gained importance. Electrical motors with superconducting rotor windings allow an increase of energy efficiency with compacter and lighter model. Since the use of first generation HTS-tape conductors has already been greatly restricted by high conductor prices, the second generation of HTS-tape conductors based on yttrium-barium-copper-oxide offer the perspective of a more economical mass production. Thus, a number of cable and motor demonstration projects were successfully realised in recent years. (EuCheMS, 2011)

High performance packaging materials

In the near future, innovation will become available such as Radio-Frequency identification tags that provide warnings for changes in temperature and humidity levels that might affect the integrity of packed products. Absorbers and emitters of natural occurring gaseous substances that prolong shelf life are already entering the market. In the future, bio-sensors that detect bacteria and viruses will pave the way for safeguarding the quality and safety of food for consumers while reducing the food waste.

8.2 Future developments

The extent to which chemical products will contribute to energy efficiency and avoided emissions during use, will depend on future economic growth, energy prices and future climate policy in the various regions, as well as the introduction of new chemical products and non-chemical alternatives to the market as discussed above. Factors impacting the development of the contribution of the European chemical industry to abatement in other sectors are:

- The development of the production of chemicals in Europe. Expressed in € sales, the European production increases by 16% between 2010 and 2050 in the Isolated Europe scenario, while it increases by 107% in the Level Playing Field scenario (Chapter 7).
- The increase in the demand for low carbon solutions in Europe will be higher in the Isolated Europe, Differentiated Global Action and Level Playing Field scenarios as compared to the Continued Fragmentation scenario, although in the Isolated Europe especially, a disappearing industrial sector in Europe could result in less demand for low carbon solutions in these sectors.

• The degree to which new innovative products from the chemical industry will take place. The level of innovation will be highest in the Differentiated Global Action and Level Playing Field scenarios, whereas in Isolated Europe, the further development of energy efficient and low carbon solutions will be hampered by the negative outlook for the European chemical industry (Chapter 7).

It is important to note that over time, the contributions to energy efficiency and the contribution to avoided emissions will develop differently, adding to the complexity of making reasonable estimates for the future contributions:

- Products in group 1 from Table 8-1 (chemical products leading to energy saving, e.g. energy
 efficient lighting) improve the energy efficiency of the sectors consuming the products. Over time,
 the electricity sector is assumed to decarbonise and the fuels applied for heating are assumed to
 become less carbon-intensive as well. As such, the products start to avoid less GHG emissions
 over time. However, by avoiding energy use during their use, the products continue to contribute
 to the feasibility and affordability of a low carbon energy system.
- Products in group 1 that are used in the agricultural sector directly contribute to avoided emissions, e.g. those related to land use changes and direct emissions from the soil. The right choice of fertilisers for example influences the N₂O and other GHG emissions during fertiliser use. A further shift to nitrate instead of urea based fertiliser has the potential to reduce agricultural emissions significantly.
- Products in group 2 from Table 8-1 (chemical products contributing to renewable electricity generation) can directly contribute to the decarbonisation of consumers' energy use and the demand for these products is quite directly linked to the decarbonisation of the energy system.

To conclude, in many existing and emerging energy efficient and low carbon solutions, products from the chemical industry play a critical role. To fully develop these technologies and introduce them into markets successfully, a strong collaboration of the important players along the value chain is necessary. A strong European chemical industry is an essential requirement for an increased development and application of low emission technologies.

9 Enabling chemistry – key conclusions and recommendations

9.1 Roadmap overview

This Roadmap explores the long-term role of the chemical industry as Europe progresses to an energy efficient and low GHG emission future. An overview of where the European chemical industry stands today in terms of product portfolio, trade position and energy and GHG emission profile is provided in Chapter 2. This is followed, in Chapter 3, by an analysis of the current policy landscape the European chemical industry faces, also in comparison with the rest of the world. The role of the chemical industry in enhancing energy efficiency and reducing GHG emissions in other sectors of the economy is discussed in Chapter 4.

The rest of the Roadmap explores the future of the European chemical industry. First, a schematic overview of the options available to the chemical industry to further improve their energy efficiency and reduce GHG emissions is given in Chapter 5. In Chapter 6, four scenarios are defined to explore the future of the European chemical industry:

In the <u>Continued Fragmentation</u> scenario, it is assumed that the current fragmented policy situation worldwide continues, with none of the key regions outside Europe taking on stringent GHG emission reduction commitments. In this scenario, Europe follows a -40% GHG emission reduction ambition for 2050 as compared to 1990.

The three other scenarios explore the implications of deep European GHG reduction ambitions for the European chemical industry. In the <u>Isolated Europe</u> scenario, Europe intensifies its policy ambitions, striving for a reduction of 80% in GHG emissions in 2050 as compared to 1990 in isolation from the rest of the world. A similar ambition level for Europe is assumed in the <u>Differentiated Global Action</u> scenario where all key economic regions take action against climate change, albeit with different policy approaches and ambition levels. Finally, the <u>Level Playing Field</u> scenario assumes a 50% global GHG reduction in 2050 as compared to 1990 combined with a similar policy burden for manufacturing industry worldwide and converging energy and feedstock prices.

The implications of these scenarios on the European chemical industry in terms of demand for chemical products, the production in Europe and the resulting trade ratio, the energy use and GHG emission profile, and the continuing role of the chemical industry as a solution provider are discussed in Chapters 7 and 8. This final Chapter summarises the key conclusions and gives recommendations to policymakers for a policy framework that stimulates sustainable and resource efficient growth in Europe.

9.2 Key conclusions

From the analyses, three key findings are extracted that are critical for the future development of the chemical industry in Europe:

Products of the chemical industry are important for all sectors of the economy to increase their energy efficiency and reduce GHG emissions. This enabling effect is likely to grow in the coming decades.

The competitiveness and growth of the European chemical industry value chain and its ability to attract investments will be damaged by isolated actions in terms of energy and climate policies, leading to rising costs to operate in Europe.

A range of current and future technologies is available to the European chemical industry to continue its long track record in energy efficiency and emissions intensity improvements. Growth and innovation are essential to achieve deep net GHG emissions reduction in the decades to come.

Products of the chemical industry are important for all sectors of the economy

While the chemical industry is a major energy user, its <u>products</u> offer solutions to save energy and reduce GHG emissions when they are used. The analysis in Chapter 4 shows that the chemical industry provides solutions for virtually all other sectors of the economy. With a further growth of existing applications and the emergence of new innovative solutions such as those explored in Chapter 8, the enabling function of the chemical industry is likely to grow in the future. This will be the case especially in the Level Playing Field and Differentiated Global Action scenarios that rely on these solutions for the deep GHG emissions reduction. The enabling solutions of the chemical industry contribute to the expected overall growth in demand for chemical products in Europe, which is estimated to grow by 150% (Isolated Europe scenario) to 200% (Level Playing Field scenario) between 2010 and 2050.

In order to achieve the full enabling potential, the European chemical industry will continue to seek enhanced cooperation with companies and other stakeholders along their value chain to foster greater uptake of chemical solutions that contribute to energy efficiency improvements and GHG emission reductions. The European chemical industry will also continue to contribute to further developing methodologies to quantify the contributions chemicals make to energy savings and overall GHG emission reductions along the value chain. This Roadmap identifies a more general need to further improve the quality and availability of energy and GHG emission data for the chemical industry. Furthermore, it would be worthwhile to further quantify GHG emission sources related to the chemical industry in Europe that are not included in the scope of the current assessment, taking a life cycle approach.

The competitiveness and growth of the European chemical industry value chain and its ability to attract investments will be damaged by isolated actions in terms of energy and climate policies Differences in energy and feedstock prices as well as divergences in energy and climate policy costs for industry determine which proportion of the growing demand for chemical products will be met by production in Europe.

The analyses show that the current energy and feedstock price differences with key competing regions outside Europe, partly due to developments in unconventional gas outside Europe, already jeopardise the competitiveness of Europe's chemical industry and the value chain it supports.

If such differences were to persist into the future, and in addition, policy cost differences were to further increase as is explored in the <u>Continued Fragmentation</u> and <u>Differentiated Global Action</u> scenarios, this would result in a negative trend in the trade balance of the European chemical industry. These scenarios foresee no further growth in petrochemicals production beyond 2030 and will result in the European Union becoming a net importer of products from the chemical industry after 2030. Given the strong value chain integration between the energy-intensive basic chemical industry and the less energy-intensive parts where basic chemicals are used, a weakening basic chemical industry will also negatively affect the other subsectors of the chemical industry. These subsectors thus also face the risk of a weakening trade ratio.

The <u>Isolated Europe scenario</u> explores the effects of a strengthened binding unilateral decarbonisation target by Europe without global action. Under this scenario, the very high policy cost differences and continued energy and feedstock price differences for industry are shown to have a deteriorating effect on the production of the energy-intensive parts of the chemical industry in Europe. They also have a strong negative effect on the production in other subsectors, as a result of the value chain integration. Ultimately, production will start to decline due to a lack of investments and potentially even divestments in Europe.

In the Continued Fragmentation, Differentiated Global Action and Isolated Europe scenarios, Europe will over time start to import more and more chemical products to meet its increasing demand. Due to increasing imports, Europe's GHG emissions will decrease, but this will happen at the expense of increased GHG emissions elsewhere due to the relocation of production. Europe's reduced emissions will not result in a net global emission reduction, and there may even be a net global increase (depending on the set-up of the European policy framework and the GHG emissions intensity of the production outside Europe). The findings show that the trend in overall GHG emissions related to consumption (including trade) can deviate compared to the trend in European emissions resulting from production only. It is therefore important to take a life cycle approach, focusing also on sustainable consumption rather than only on sustainable production in Europe.

The <u>Level Playing Field</u> scenario explores how the European chemical industry could develop under conditions of converging energy and feedstock prices and similar policy costs for manufacturing industry globally. Under such conditions, the European chemical industry will continue to attract investments to meet the growing demand with production in Europe while reducing its GHG emissions intensity as it did in the past. Estimates from previous studies show that between 1990 and 2010, the European chemical industry halved its GHG emissions while still attracting investments. Such a

growing chemical industry will continue to create value and deliver high quality jobs to Europe's society. Figure 9-1 and Figure 9-2 give a summarising overview of the range in demand for chemical products, the production and the trade ratio in the scenarios studied.



Figure 9-1 EU demand for and production of chemical products (expressed in 2010 € of sales). All scenarios show rising demand for chemical products. However, production substantially shifts outside Europe in the absence of a level playing field



Figure 9-2 Net trade ratio expressed as net export as % of demand. Unilateral action will result in significant import dependence for chemical products with no overall reduction of greenhouse gas emissions

A range of technologies is available to the European chemical industry to continue its long track record in energy efficiency improvements and GHG emission reduction

There are a range of current and future technologies to improve energy efficiency and reduce the GHG emissions of the chemical industry. It is clear that further innovations are required to achieve deep reductions in GHG emissions. Important research areas include advanced biomass conversion processes, further process improvements, and the utilisation of carbon dioxide as raw material (Carbon Capture and Utilisation, CCU).

Regardless the scenario studied, continued energy efficiency improvements will contribute most to further reductions in the GHG emissions intensity of the chemical industry. Under the <u>Level Playing</u> <u>Field</u> scenario, the production growth towards 2050 will be more or less offset by these efficiency gains, resulting in only a slight increase in energy use towards 2050.

However, it should be noted that the potential for further energy efficiency improvements varies between different subsectors, different regions within the EU and different chemical sites. The basic chemical industry uses mature technologies that sometimes already operate close to the thermodynamic minimum and as such offer limited further potential. For some products studied in this Roadmap, however, substantial differences were found between the best and worst performing plants, which shows that there is still significant potential for some sites to improve. On average, the energy intensity per unit of sales could decrease by about 25% in the period between 2010 and 2030, but this average cannot be applied to all individual sites, countries or subsectors. Moreover, further innovations are needed to achieve these improvements.

A change in the fuel mix used for heat generation is another important option to reduce the GHG emissions intensity of the chemical industry in Europe. This route also relies on further innovations. There is potential to increase the use of biomass up to a maximum share of about 10% in 2030. However, part of the GHG emission reductions achieved in the chemical industry through the increased use of biomass could be offset by GHG emissions from the cultivation of biomass, which can be substantial for some biomass types. It is important to consider the overall life cycle GHG emissions balance of biomass (including indirect land use change effects) when assessing the overall sustainability related to biomass, to a much more limited extent, geothermal heat can also be used to lower GHG emissions intensity in the chemical industry.

A third important option for the chemical industry to reduce GHG emissions is the abatement of N_2O from the production of nitric acid and some other chemical products. The abatement of these emissions becomes economically viable already at moderate CO_2 prices. An almost complete N_2O abatement is projected in all scenarios for the coming decade.

Energy efficiency, changes in fuel mix for heat generation and N_2O abatement are options that are largely under control of the chemical industry itself. In a <u>Level Playing Field</u> scenario, these options together have the potential to reduce the GHG emissions intensity of the chemical industry by 55% in 2050 as compared to the 2010 GHG emissions intensity. In absolute terms, under the <u>Level Playing Field</u> scenario, the options discussed so far could reduce GHG emissions by 15% in 2030 as compared to 2010. Emissions would stabilise around these levels towards 2050, building on the already achieved reduction of 50% in 2010 as compared to 1990. In the three other scenarios (<u>Isolated Europe, Continued Fragmentation</u> and <u>Differentiated Global</u> <u>Action</u>), higher absolute GHG emission reductions are projected in Europe, but at the expense of relocation of production outside of Europe. This would happen with no overall reduction in global GHG emissions or even a potential increase as discussed above.

Furthermore, in relative terms, the scenarios of isolated EU action, in which there is no global action to tackle climate change (<u>Isolated Europe, Continued Fragmentation</u>), result in lower reductions in GHG emissions intensity compared to the <u>Level Playing Field</u> scenario. Among other reasons, this is due to limited growth in Europe and relocation of industry to outside Europe. Deep reductions in GHG emissions intensity will only be realised if industry has the confidence to invest in Europe. This is confirmed by analyses in this Roadmap, which show very limited improvements in energy efficiency in the last decade for some important large volume chemicals that provide the foundation for the chemical industry value chain.

Deeper reductions in GHG emissions are possible by decarbonising the electricity production in Europe and by applying carbon capture and storage (CCS) to emissions from the chemical industry. These options are costly and require technological breakthroughs. They face several barriers that can only to a limited extent be steered by the chemical industry itself. For CCS, these barriers include the lack of public acceptance, the large infrastructure requirements needed and questions around the feasibility and cost-effectiveness of the technology for smaller, dispersed emission sources. Decarbonising the electricity sector comes with challenges related to grid and other infrastructure requirements to incorporate a large share of intermittent renewable electricity sources.

This Roadmap also assessed the options to reduce the fossil feedstock requirement and identified potentials for bio-based feedstock and increased use of recycled products.

9.3 Policy recommendations

In the absence of an international climate change agreement, the future of the chemical industry in Europe depends on smart policies that avoid further policy-induced energy cost burdens. Strengthening external relations with other regions, further diversifying energy supply and ensuring a well-functioning integrated energy market is essential for more globally competitive industrial energy prices in Europe.

This Roadmap reveals that the current policy framework in Europe poses a threat to the competitive position of the European chemical industry. The free allocation of emission allowances in the EU emissions trading system (EU ETS) is a measure to support the competitive position of the industry and to maintain production in Europe. However, the allocation is determined ex-ante, using historical production, which could limit the efficient growth of the chemical industry in Europe. Furthermore,

uncertainties about full compensation for CO_2 costs in the electricity price erode investments and growth perspectives and affects EU global competitiveness. These drawbacks could be overcome by moving to a more dynamic EU ETS with an allocation based on actual production and including indirect emissions. This would offer a long-term perspective for investments in new installations and is possible while maintaining an absolute GHG emission cap in the scheme.

The costs related to a more renewable energy supply system rise in all decarbonisation scenarios. These costs include support for renewable energy generation and costs related to back-up facilities, storage and grid connections. The regional workshops organised in the context of this Roadmap made clear that the currently non-coordinated and in some cases excessive support for renewable electricity results in additional cost burdens to the European chemical industry. This renewable energy support and the cost pass-through to industry should be better coordinated and take into account the cost build-up for electricity in key competing regions outside Europe.

There is a risk that European energy and climate policies overlap, resulting in a sub-optimal and ineffective policy package. The review of the European Energy Taxation directive and the implementation of the Energy Efficiency Directive as well as the overall design of the post-2020 policy package should minimise sub-optimal solutions.

Energy security, competitive energy prices and climate protection are all important pillars of European policy. Currently, European policymaking is at a crossroads. Notably in an Isolated Europe approach, supporting the competitive position of European industry and the associated growth and job creation could be at conflict with climate policy ambitions that aimed for a much faster transformation to a low carbon economy than other major global regions. The European chemical industry recognises this tension and calls on policymakers to provide:

An effective framework to maintain competitiveness on the route towards global action

- Europe should continue its efforts towards global rather than unilateral action against climate change.
- In the absence of a global climate change agreement, the design of the carbon market and further climate policy post-2020 should be further improved to promote efficient production and production growth in Europe.
- Measures to support the competitive position of the European chemical industry should be stable, predictable and coordinated across Europe. They should also avoid unnecessary cost burdens to European industry. Furthermore, the framework should be designed to incentivise the innovations required for deep GHG emissions reduction.

<u>A European energy policy to ensure a diversified and competitive energy supply</u>

- A truly European energy policy should be developed, including fully integrated and wellfunctioning electricity and natural gas markets.
- This energy policy should guarantee a diverse and more competitive energy supply in Europe and allow for sustainable exploration of new forms of energy such as unconventional gas.

• Renewable energy support schemes should be simplified and more coordinated across Europe. Policy makers should direct the energy portfolio towards cost-effective renewable and alternative energy options that can serve our energy needs without excessive additional back-up capacity and infrastructure costs.

<u>Policy approaches that acknowledge the vital role of the chemical industry in sustainable consumption</u> <u>patterns</u>

- The policy framework should take into account the role of the chemical industry in enabling energy efficiency and economy-wide GHG emissions reduction.
- Sustainable consumption should be further incentivised, focusing on the full life cycle performance of products and applications, taking on board the latest developments in methodologies.

<u>An R&D and innovation framework towards market-oriented and cost-efficient technology</u> <u>development</u>

- Research and development support for innovation should facilitate new breakthrough technologies in pre-competitive phases and should focus on innovative solutions across the borders of individual sectors. Cross sector cooperation is vital in the field of further energy efficiency improvements and in the area of new innovative product solutions.
- The policy package should enable market-oriented, cost-efficient technologies. It should help to overcome barriers such as public acceptance to and regulatory uncertainties surrounding new innovative technologies.
- A suitable support framework for the development of bio-based chemistry should be developed via standardisation of sustainability criteria for biomass, stimulation of cascaded biomass use and elimination of import duties.
- Adequate financing schemes for the adoption of energy efficient and low carbon technologies should be developed.

To conclude, long-term action by all stakeholders is critical to realise a low carbon and energy efficient future. Governments should help to create a favourable environment that encourages additional gains in efficiency and lowers energy use and emissions, while keeping a strong chemical industry in Europe. Industry should highlight priorities for support, accelerate capital investments as well as research and development, and prompt further focused collaborations with academia and government research laboratories.

List of abbreviations

APPE	Association of Petrochemicals Producers in Europe
ASU	Air separation unit
ВАТ	Best available techniques
CAGR	Compound annual growth rate
CCS	Carbon capture and storage
CCSU	Carbon capture, storage and utilisation
CCU	Carbon capture and utilisation
CFL	Compact fluorescent lamp
СНР	Combined heat and power
CITL	Community Independent Transaction Log
CO ₂	Carbon dioxide
CSF	Cross-sectoral correction factor
DMT	Dimethyl terephthalate
EC	European Commission
EED	Energy Efficiency Directive
EPS	Expanded polystyrene
ETS	Emissions trading system
EUA	European Union emission allowance
EuCheMS	European Association for Chemical and Molecular Sciences
GDP	Gross domestic product
GHG	Greenhouse gas

HSE	Health, Safety and Environment
HTS	High temperature superconductors
ICCA	International Council of Chemical Associations
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
II	Joint Implementation
LDPE	Low-density polyethylene
LED	Light emitting diode
MEG	Mono-ethylene glycol
MILP	Mixed integer linear programming
МТО	Methanol-to-Olefins
NAFTA	North American Free Trade Agreement
N ₂ O	Nitrous oxide
NACE	Statistical Classification of Economic Activities in the European Community
NER	New entrants' reserve
NH ₃	Ammonia
NO	Nitric oxide
NO ₂	Nitrogen dioxide
O&M	Operations and maintenance
ODC	Oxygen-depolarised cathode
OLED	Organic light emitting diodes
ORC	Organic Rankine Cycle
PE	Polyethylene

PEFC	Polymer electrolyte fuel cell
PET	Polyethylene terephthalate
РНА	Polyhydroxyalkanoates
PI	Process intensification
PLA	Polylactic acid
РММА	Polymethyl methacrylate
РРР	Public private partnerships
РТА	Purified terephthalic acid
PU	Polyurethane
PVC	Polyvinylchloride
R&D	Research and development
RIC	Resign Identification Code
SMR	Steam methane reforming
SSAS	Solid State Ammonia Synthesis
UIC	L'Union des Industries Chimiques (French chemical industries association)
UNFCCC	United Nations Framework Convention on Climate Change
VCI	Verband der Chemischen Industrie e.V. (German chemical industries association)
VIP	Vacuum insulated panel
VSD	Variable-speed drive
WBCSD	World Business Council for Sustainable Development
XPS	Extruded polystyrene

References

ACCR, 2004 *Good Practices Guide on Waste Plastics Recycling – a guide by and for local and regional authorities,* The Association of Cities and Regions for Recycling (ACCR)

AEC, 2012 Cellulosic Biofuels – Industry progress report 2012-2013, Advanced Ethanol Council (AEC), December 2012

Agreda, V.H. and Cwirko, E.H., 2007 *Process Itensification (PI) at Eastman Chemical Company,* Eastman, presentation for AgentschapNL, May 2007 (available at <u>http://www.agentschapnl.nl/sites/default/files/bijlagen/Reactive_Distillation-Agreda_20070502.pdf</u>)

Alliance, 2007 *Lowering Production is no Benefit for the Environment, says European Industry*, Alliance of Energy Intensive Industries (AEII) in Europe, May 2007

Alliance, 2011 The Alliance of Energy Intensive Industries (AEII) urges the European Commission and Member States to bring the Guidance Documents on allocation in line with the draft Commission Decision and with the EU ETS Directive, Alliance of Energy Intensive Industries (AEII) in Europe, March 2011

APPE, 2012 *Petrochemicals make things happen,* Association of Petrochemicals Producers in Europe (APPE) (available at <u>http://www.petrochemistry.net/</u>)

Bach, P.W., 2007, *Van restwarmte naar proceswarmte*, Energy research Centre of the Netherlands (ECN), Amsterdam, Netherlands (available at <u>http://www.ecn.nl/docs/library/report/2007/l07071.pdf</u>)

Berghout, N., van den Broek, M.A., and Faai, A. (forthcoming) *Techno-economic performance and challenges of applying CO2 capture in the industry - A case study of five industrial plants*, International Journal of Greenhouse Gases

Blomen, E., Hendriks, C., and Neele, F., 2009 *Capture technologies: Improvements and promising developments*, Energy Procedia Volume 1, Issue 1, February 2009, pp. 1505–1512

BMBF, 2012 *Germany's research funding programme on CO2 utilization*, Presentation from Lothar Mennicken during CO₂ reuse workshop organised, German Federal Ministry of Education and Research (BMBF), October 2012 (Available at <u>http://www.CO2reuse.eu/images/stories/pdf-files/7-Mennicken CO2reuse German Programme Oct2012.pdf</u>)

Böringer, C., Fischer, C. and Rosendahl, K.E., 2010 *The Global Effects of Subglobal Climate Policies*, Resources for the Future discussion paper 10-48, Washington, USA, October 2010

BP, 2012 *Statistical Review of World Energy 2012*, BP, June 2012 (Available at http://www.bp.com/sectionbodycopy.do?categoryId=7500&contentId=7068481)

Brandt, B. and Pilz, H., 2011 *The impact of plastic packaging on life cycle energy consumption and greenhouse gas emissions in Europe,* denkstatt, report for PlasticsEurope, Vienna, Austria, July 2011

Braskem, 2008 *Press statement: Braskem approves green polyethylene project* (available at http://www3.braskem.com.br/site/portal_braskem/en/sala_de_imprensa/sala_de_imprensa_detalhes_8129.aspx)

Brems, A., Bayens, J., and Dewil, R. 2012 *Recycling and Recovery of Post-Consumer Plastic Solid Waste in an European Context*, Thermal Science, Year 2012, Vol. 16, No. 3, pp. 669-685

BREW, 2006, *Medium and Long-term Opportunities and Risks of the Biotechnological Production of Bulk Chemicals from Renewable Resources - The Potential of White Biotechnology*, The Brew Project, report for the European Commission DG Research, Utrecht, Netherlands, September 2006

Broek, M. A. van den, 2010 *Modelling approaches to assess and design the deployment of CO*₂ *capture, transport, and storage,* PhD thesis, Department of Science, Technology and Society, Faculty of Science, Utrecht University, Utrecht, August 2010

Broek, M. van den, Hoefnagels, E.T.A., Rubin, E., Turkenburg, W.C., and Faaij, A.P.C., 2009 *Effects of technological learning on future cost and performance of power plants with CO2 capture,* Progress in Energy and Combustion Science 35(6), pp. 457-480

Building Up, 2012 Deliverable D3.2: Roadmap – Multi-stakeholder, Cross-sectorial, Collaborative long term Research and Innovation Road Map to overcome Technological and Non-technological barriers towards more energy-efficient buildings and districts, September 2012 (available at http://www.buildingup-e2b.eu/documents/24430/25374/Building-Up+Roadmap%3A+FINAL+version)

Burniaux, J. et al., 2008 *The Economics of Climate Change Mitigation: Policies and Options for the Future*, Organisation for Economic Co-operation and Development (OECD) Economics Department Working Papers, No. 658, OECD Publishing. <u>http://dx.doi.org/10.1787/228868001868</u>

Carbon Trust, 2010 *Tackling carbon leakage, Sector-specific solutions for a world of unequal carbon prices*, London, March 2010

Carbon Trust, 2012 *Polymer Fuel Cells – Cost reduction and market potential*, report for the Department for Energy and Climate Change (DECC) UK, London, United Kingdom, September 2012

Carus, M., 2012 *Bio-based Economy in the EU-27: A first quantitative assessment of biomass use in the EU industry*, nova-Institut, Hürth, Germany

CBS, 2012 *Environmental accounts of the Netherlands – Greenhouse gas emissions by Dutch economic activities*, Statistics Netherlands (CBS), the Hague/Heerlen, Netherlands

Cefic, 2012a *Facts and Figures 2012 and additional analyses*, The European Chemical Industry Council (CEFIC), Brussels, Belgium, 19 December 2012

Cefic, 2012b Cefic contribution to consultation on EC proposals of 25 July 2012 on "fixing" the ETS/"backloading", Brussels, Belgium, 3 October 2012

Cefic, 2013 *Cefic contribution to consultation EC Carbon Market Report*, The European Chemical Industry Council (CEFIC), Brussels, Belgium

ChemData, 2012 *Cefic Chemdata International 2012*, The European Chemical Industry Council (CEFIC), Brussels, Belgium

Chemicals-technology.com, 2013 Algenol Biofuels Pilot-Scale Integrated Bio-Refinery, Florida, United States of America, Projects, Industry Projects (available at http://www.chemicals-technology.com/projects/algenol-biofuels-integrated-bio-refinery-florida/)

Chidichimo, G., and Filippelli L., 2010 *Organic Solar Cells: Problems and Perspectives*, International Journal of Photoenergy Volume 2010 (2010), Dipartimento di Chimica, Università degli Studi della Calabria, 87036 Arcavacata di Rende, Italy, May 2010

COGEN Europe, 2013 *European Cogeneration Review – The Netherlands,* COGEN Europe, Brussels, Belgium, January 2013

Consultic, 2012 *Post-consumer Plastic Waste Management in European countries 2011*, final report, Consultic Marketing & Industrieberatung GmbH, Azenau, Germany

Cornelissen, S., Koper, M., and Deng, Y., 2012 *The role of bioenergy in a fully sustainable global energy system, Biomass and Bioenergy*, Volume 41, June 2012, pp. 21–33

Creative Energy, 2007 *European Roadmap for Process Intensification,* Creative Energy, December 2007

Damen, K., 2007 *Reforming Fossil Fuel Use – the merits, costs and risks of carbon dioxide capture and storage*, PhD thesis, Department of Science, Technology and Society, Faculty of Science, Utrecht University, Utrecht, Netherlands

Dröge, S. 2009 *Tackling Leakage in a World of Unequal Carbon Prices*, Climate Strategies, September 2009

ECF, 2010 *Biomass for heat and power – Opportunity and Economics*, European Climate Foundation (ECF), Brussels, Belgium, June 2010

ECN, 2004 *Energietechnologieën in het kader van transitiebeleid – Factsheets*, Energy research Centre of the Netherlands (ECN), Petten, Netherlands, February 2004

Ecofys, 2008 The IFIEC method for the allocation of CO_2 allowances in the EU Emissions Trading Scheme – a review applied to the electricity sector, Utrecht, Netherlands, March 2008

Ecofys, 2009 Sectoral Reduction Potentials and Economic Costs for Climate Change (SERPEC-CC) database, Consortium of Ecofys (lead partner), ICCS NTUA, IPTS JRC, AEA Energy and Environment, CE-Delft, report for the European Commission, Utrecht, Netherlands

Ecofys, 2012, *Climate protection with rapid payback Energy and emissions savings potential of industrial insulation in EU27*, report for the European Industrial Insulation Foundation, Geneva/Utrecht, June 2012

Ecofys, Fraunhofer, Öko-Institut, 2009 *Methodology for the free allocation of emission allowances in the EU ETS post 2012, sector report for the chemical industry*, report for the European Commission, Ecofys, Utrecht, Netherlands.

Ecofys-WWF, 2011 *The Energy Report – 100% Renewable Energy by 2050*, collaboration of Ecofys and Worldwide Wildlife Fund (WWF), February 2011.

Edison Tech Center, 2010 LEDs and OLEDs (available at http://www.edisontechcenter.org/LED.html)

EEA, 2013 *The European Pollutant Release and Transfer Register (E-PRTR),* European Environment Agency (EEA) (available at <u>http://prtr.ec.europa.eu/</u>)

EPA, 2012 *Waste Heat to Power Systems,* United States Environmental Protection Agency (EPA) Combined Heat and Power Partnership, Washington DC, USA (available at <u>http://www.epa.gov/chp/documents/waste_heat_power.pdf</u>)

EuCheMS, 2011 *Chemistry – Developing Solutions in a Changing World*, European Association for Chemical and Molecular Sciences (EuCheMS), Brussels, Belgium, May 2011

European Commission, 2003 *COUNCIL DIRECTIVE 2003/96/EC of 27 October 2003 restructuring the Community framework for the taxation of energy products and electricity*, L283/51, Brussels, Belgium, October 2003 (available from: <u>http://eur-</u> lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2003:283:0051:0070:EN:PDF)

European Commission, 2009 *DIRECTIVE 2009/28/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC, L 140/16, Brussels, Belgium, June 2009 (available from: <u>http://eur-</u>*

lex.europa.eu/LexUriServ/LexUriServ.do?uri=Oj:L:2009:140:0016:0062:en:PDF)

European Commission, 2010 REPORT FROM THE COMMISSION TO THE COUNCIL AND THE EUROPEAN PARLIAMENT on sustainability requirements for the use of solid and gaseous biomass sources in electricity, heating and cooling, COM(2010)11 final, Brussels, Belgium, February 2010 (available at http://eur-

lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:52010DC0011:EN:HTML:NOT)

European Commission, 2011a A roadmap for moving to a competitive low carbon economy in 2050, COM (2011) 112 final, Brussels, Belgium, March 2011 (available at http://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:52011DC0112:EN:NOT)

European Commission, 2011b Energy Roadmap 2050, COM (2011) 885 final, Brussels, Belgium, December 2011 (available at http://ec.europa.eu/energy/energy2020/roadmap/doc/roadmap2050 ia 20120430 en.pdf)

European Commission, 2011c Best Available Techniques (BAT) Reference Document for the Production of Chlor-alkali Industrial Emissions, Integrated Pollution Prevention and Control (IPPC), December 2001

European Commission, 2012a COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS A stronger European Industry for Growth and Economic Recovery Industrial Policy Communication Update, COM (2012) 582 final, Brussels, Belgium, 10 October 2012 (available at http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2012:0582:FIN:EN:PDF)

European Commission, 2012b REPORT FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT AND THE COUNCIL The state of the European carbon market in 2012, COM(2012) 652 final, Brussels, Belgium, November 2012 (available at

http://ec.europa.eu/clima/policies/ets/reform/docs/com 2012 652 en.pdf)

European Commission, 2012c, Proposal for a Directive amending Directive 98/70/EC relating to the quality of petrol and diesel fuels and amending Directive 2009/28/EC on the promotion of the use of energy from renewable sources, COM(2012) 595 final, Brussels, Belgiu, December 2012 (available at http://ec.europa.eu/clima/policies/transport/fuel/docs/com 2012 595 en.pdf)

European Commission, 2012d DIRECTIVE 2012/27/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC, L315/1, Brussels, Belgium, November 2012 (available at http://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:315:0001:0056:EN:PDF)

Eurostat, 2007 Multi-year enterprise statistics - purchases of energy products and annual detailed enterprise statistics on manufacturing sub-sections, Structural Business Statistics

Eurostat, 2012a *Extra-EU27 trade, by main partners, total product,* database '*tet00040*' (available at http://epp.eurostat.ec.europa.eu/tgm/table.do?tab=table&init=1&plugin=1&language=en&pcode=tet 00040)

Ganley, J.C. Holbrook, J.H., and McKinley, D.E., 2007 *Solid State Ammonia Synthesis*, NHThree LLC, Ammonia – A Sustainable, Emission-Free Fuel, October 2007 (available at http://nh3fuel.files.wordpress.com/2012/05/ssas_oct2007_final.pdf)

Greenpeace, 2010 Energy [r]evolution 2010: A Sustainable World Energy Outlook, report for Greenpeace by the European Renewable Energy Council (EREC) and Global Wind Energy Council (GWEC), June 2010

Grubb, M., Brewer, T.L., Sato, M., Heilmayr, R., and Fazekas, D., 2009 *Climate Policy and Industrial Competitiveness: Ten Insights from Europe on the EU Emissions Trading System*, Climate & Energy Paper Series 09, commissioned by The German Marshall Fund of the United States.

Hanegraaf, M. and Spaans, H., 2012 *Carbon Capture & Utilization en de potentie voor de (chemische) industrie in Nederland*, SPPS consultants, Breda, Netherlands (available at <u>http://www.routekaartchemie.nl/images/2012-11/spps-over-potentie-ccu.pdf</u>)

Hübler, M. and Löschel, A., 2012 *The EU Decarbonisation Roadmap 2050 What Way to Walk?*, Zentrum für Europäische Wirtschaftsforschung (ZEW), ZEW Discussion Paper No. 12-055, Mannheim, Germany, May 2012

ICCA, 2009 Innovations for Greenhouse Gas Reductions — A life cycle quantification of carbon abatement solutions enabled by the chemical industry, International Council of Chemical Associations (ICCA), July 2009

ICCA, 2012 ICCA Building Technology Roadmap – Chemical industry contributions to energy and greenhouse gas savings in residential and commercial construction, International Council of Chemical Associations (ICCA), November 2012

ICF, 2012 *An international comparison of energy and climate change policies impacting energy intensive industries in selected countries*, ICF International, report for UK Department for Business Innovation & Skills, London, United Kingdom, July 2012

IEA and UNIDO, 2011 *Technology Roadmap – Carbon Capture and Storage in Industrial Applications*, International Energy Agency (IEA), United Nations Industrial Development Organization (UNIDO)

IEA, 2009a *Chemical and Petrochemical Sector - Potential of best practice technology and other measures for improving energy efficiency*, International Energy Agency, Paris, France, September 2009 IEA, 2009b Energy Technology Transitions For Industry - Strategies for the Next Industrial Revolution, International Energy Agency, Paris, September 2009

IEA, 2010a *Technology Roadmap: Geothermal Heat and Power*, International Energy Agency (IEA), Paris, France, June 2011 (available at http://www.iea.org/publications/freepublications/publications/publication/Geothermal Foldout.pdf)

IEA, 2010b *Technology Roadmap: Concentrating Solar Power*, International Energy Agency (IEA), Paris, France, May 2010 (available at http://www.iea.org/publications/freepublications/publication/csp roadmap.pdf)

IEA, 2011a *Technology Roadmap – Biofuels for transportation*, International Energy Agency (IEA), Paris, France, April 2011

IEA, 2011b *Energy-Efficiency Policy Opportunities for Electric Motor-Driven Systems*, International Energy Agency, Paris, France, May 2011

IEA, 2011c *Global Wood Pellet Industry Market and Trade Study*, International Energy Agency (IEA) Bioenergy, Task 40: Sustainable International Bioenergy trade, Paris, France, December 2011

IEA, 2012a *Key World Energy Statistics 2012 – Extended Energy balance EU-27*, International Energy Agency (IEA), Paris, France, September 2012

IEA, 2012b. *Bio-based Chemicals, Value Added Products from Biorefineries*, International Energy Agency (IEA) Bioenergy, Paris, France, February 2012

IEA, 2012c *Energy Technology Perspectives 2012*, International Energy Agency (IEA), Paris, France, June 2012

IEA, 2012d *World Energy Outlook 2012,* International Energy Agency (IEA), Paris, France, November 2012

IFPRI, 2011 Assessing the Land Use Change Consequences of European Biofuel Policies, International Food Policy Research Institute (IFPRI), October 2011 (Available from http://trade.ec.europa.eu/doclib/docs/2011/october/tradoc_148289.pdf)

IIP, 2012 *Industrial efficiency policy database*, Institute for Industrial Productivity (IIP) (available at http://iepd.iipnetwork.org/)

IPCC, 2006 *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, Intergovernmental Panel on Climate Change (IPCC), prepared by the National Greenhouse Gas Inventories Programme, Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., and Tanabe, K. (eds), Institute for Global Environmental Strategies (IGES), Japan IPPC, 2007 *IPCC Fourth Assessment Report: Climate Change 2007 (AR4),* Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge, United Kingdom and New York, USA

IPPC, 2011 Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN), Chapter 4 Geothermal Energy, Intergovernmental Panel on Climate Change (IPCC) Working Group III, Abu Dhabi, UAE, May 2011 (available at <u>http://srren.ipcc-wg3.de/report/IPCC_SRREN_Ch04.pdf</u>)

IRENA, 2013 *Production of Bio-ethylene – Technology Brief*, Energy Technology Systems Analysis Programme of the International Energy Agency (IEA-ETSAP) and International Renewable Energy Agency (IRENA), Abu Dhabi, UAE, January 2013 (available at <u>http://www.irena.org/DocumentDownloads/Publications/IRENA-</u> <u>ETSAP%20Tech%20Brief%20I13%20Production of Bio-ethylene.pdf</u>)

Keulenaer, H. de, Belmans, R., Blaustein, E., Chapman, D., Almeida, A. de, Wachter, B. de, and Radgen, P., 2004 *Motor Challenge Programme – Energy Efficient Motor Driven Systems,* published by European Copper Institute, Brussels, Belgium, April 2004

Kuramochi, T., 2011, *CO*₂ *capture in industries and distributed energy systems: Possibilities and limitations,* Science, Technology & Society, PhD Thesis, Utrecht University, Utrecht, Netherlands

Linnhoff-March, 2000 The Methodology and Benefits of Total Site Pinch Analysis

Manders, T. and Veenendaal, P., 2008 *Border tax adjustments and the EU-ETS, A quantitative assessment*, CPB Netherlands Bureau for Economic Policy Analysis / Netherlands Environmental Assessment Agency, CPB Document No 171, Den Haag, Netherlands, October 2008

McKinsey, 2009, *Pathways to a Low-Carbon Economy, Version 2 of the Global Greenhouse Gas Abatement Cost Curve*, McKinsey & Company, January 2009

Monforti, F., Bódis, K., Scarlat, N., and Dallemand J.-F., 2013 *The possible contribution of agricultural crop residues to renewable energy targets in Europe: A spatially explicit study*, European Commission, JRC, Institute for Energy and Transport, Renewable Energy Unit, Renewable and Sustainable Energy Reviews, v. 19, March 2013, p. 666-677

NanoMarkets, 2011 The Future of Conductive Polymers: Room for Improvement, Advanced Materials (available at

http://nanomarkets.net/articles/article/the future of conductive polymers room for improvement)

Neelis, M. Worrell, E., and Masanet, E., 2008 *Energy Efficiency Improvement and Cost Saving Opportunities for the Petrochemical Industry*, Ernest Orlando Lawrence Berkeley National Laboratory, Environmental Energy Technologies Division, Berkeley, USA, June 2008 Neelis, M., Patel, M., Blok, K., Haije, W. and Bach, P. (2007) *Approximation of theoretical energy saving potentials for the petrochemical industry using energy balance for 68 key processes,* Energy, Vol. 32, pp. 1104-1123

OECD, 2012 Addressing Competitiveness And Carbon Leakage Impacts Arising From Multiple Carbon Markets: A Modelling Assessment, Organisation for Economic Co-operation and Development (OECD) Working Party on Climate, Investment and Development, OECD Headquarters, Paris, France, September 2012

OECD/FAO, 2012 *OECD-FAO Agricultural Outlook 2012-2021*, Organisation for Economic Co-operation and Development (OECD) – Food and Agriculture Organization of the United Nations (FAO), OECD Publishing and FAO, July 2012 (available at <u>http://dx.doi.org/10.1787/agr_outlook-2012-en</u>)

Open Source Nanotech Initiative, 2013 Open Source Aerogel (available at http://www.aerogel.org/)

Parsons Brinckerhoff/GCCSI, 2011 Accelerating the uptake of CCS: Industrial use of captured carbon dioxide, report for the Global CCS Institute (GCCSI), March 2011

Pilz, H., Brandt, B. and Fehringer, R., 2010 *The impact of plastics on life cycle energy consumptions and greenhouse gas emissions in Europe,* denkstatt, report for PlasticsEurope, Vienna, Austria, June 2010

PlasticsEurope, 2011 *Plastics – The Facts 2011, An analysis of European plastics production, demand and recovery for 2010, PlasticsEurope, Brussels, Belgium, November 2011*

Platts, 2012 T2 FOB Rotterdam Ethanol quotes

Policy Exchange, 2010 *UK consuming a third more CO*₂ *than in 1990*, press release 19 November 2010 (available at <u>http://www.policyexchange.org.uk/media-centre/press-releases/category/item/uk-consuming-a-third-more-co2-than-in-1990)</u>

PSI, 2012 Information provided in the context of this Roadmap on Energy Efficiency Improvement of Ammonia production, Plant Surveys International (PSI)

PTAI, 2013 Information provided in the context of this Roadmap on Energy Efficiency Improvement of *Polymers production*, Philip Townsend Associates (PTAI)

Rafiqul, I., Weber, C., Lehmann, B., and Voss, A., 2005 *Energy efficiency improvements in ammonia production – perspectives and uncertainties*, Energy Vol 30, Issue 13, p. 2487-2504

Reinaud, J., 2008 *Issues behind Competitiveness and Carbon Leakage – Focus on Heavy Industry*, International Energy Agency (IEA) information paper, Organisation for Economic Co-Operation and Development (OECD)/IEA, October 2008 Ren, T., 2009 *Petrochemicals from Oil, Natural Gas, Coal and Biomass: Energy Use, Economics and Innovation*, PhD thesis, Department of Science, Technology and Society, Faculty of Science, University Utrecht, Utrecht, Netherlands, March 2009

RE-Shaping, 2012, *RE-Shaping – Shaping an effective and efficient European renewable energy market*, a report for the European Commission compiled within the European research project RE-Shaping <u>www.reshaping-res-policy.eu</u> supported by Intelligent Energy – Europe, Karlsruhe, Germany, February 2012

Rubin, E. S., Chen, C., and Roa, A.B. 2007 *Cost and performance of fossil fuel power plants with CO2 capture and storage,* Energy Policy 35(9), p. 4444-4454

Saygin, 2012 Assessing industrial energy use and CO2 emissions – Opportunities for energy, efficiency, biomass and CCS, PhD thesis Utrecht University, Utrecht, Netherlands, December 2012

Saygin, D., Patel, M.K., Worrell, E., Tam, C., and Gielen, D.J., 2011 *Potential of best practice technology to improve energy efficiency in the global chemical and petrochemical sector*, Energy, 36(9), p. 5779-5790

Scheirs, J. and Long, T.E. (eds), 2003 *Modern Polyesters: Chemistry and Technology of Polyesters and Copolyesters,* Jonn Wiley & Sons, October 2003

Schyns, V., Stalmans, L., and Brouwers, E., 2012 *A reality check of the EU Emissions Trading Scheme: Does it allow growth – the major objective of the EU industry policy?*, collaboration with The European Chemical Industry Council (CEFIC) and the International Federation of Industrial Energy Consumers (IFIEC) Europe, Brussels, Belgium

Shell, 2013 New Lens Scenarios - a Shift in Perspective for a World in Transition, March 2013

Shen, L., 2011 *Bio-based and Recycled Polymers for Cleaner Production – An assessment of plastics and fibres*, PhD thesis, University Utrecht, Utrecht, Netherlands, March 2011

Smeets, E., 2008 *Possibilities and limitations for sustainable bioenergy production systems,* PhD Thesis, University Utrecht, Utrecht, Netherlands, July 2008

SPIRE, 2012 SPIRE Roadmap – Consultation Document, Sustainable Process Industry through Resource and Energy Efficiency (SPIRE), Brussels, Belgium, November 2012

Stankiewicz, A., 2007 *Process Intensification: The Chance Europe Cannot Afford to Miss* European Federation of Chemical Engineering (EFCE) Working Party on Process Intensification, Delft, Netherlands, January 2007

Star-COLIBRI, 2011a *European Biorefinery Joint Strategic Research Roadmap for 2020*, Strategic Targets for 2020 – Collaboration Initiative on Biorefineries (Star-COLIBRI), Brussels, Belgium, October 2011

Star-COLIBRI, 2011b *Joint European Biorefinery Vision for 2030*, Strategic Targets for 2020 – Collaboration Initiative on Biorefineries (Star-COLIBRI), Brussels, Belgium, October 2011

Strong, A.B. and Lunt, B.M., 2001 CONDUCTIVE POLYMERS: WHY THEY WERE WORTH THE NOBEL PRIZE, Brigham Young University

Styring, P., Jansen, D., de Coninck, H., Reith, H. and Armstrong, K., 2011 *Carbon Capture and Utilisation in the green economy: using CO2 to manufacture fuel, chemicals and materials*, The University of Sheffield and Energy research Centre of the Netherlands (ECN), report for Centre for Low Carbon Futures, Sheffield, United Kingdom, 2011

Summerton, P., 2010 Assessment of the degree of carbon leakage in light of an international agreement on climate change, a report for the Department of Energy and Climate Change (DECC) UK, Cambridge Econometrics, Climate Strategies and Entec UK, 19 August 2010

SusChem, 2010 SusChem Hybrid Materials Workshop Report: Setting the future materials research agenda for Sustainable Chemistry, European Technology Platform for Sustainable Chemistry (SusChem) and Dutch Polymer Institute (DPI), Luxembourg, March 2010.

U.S. DOE, 2013 *Hydrogen Production*, Hydrogen and Fuel Cells Program, United States Department of Energy (U.S. DOE) (available at <u>http://www.hydrogen.energy.gov/production.html</u>)

UNEP, 2012 *Conversion from Mercury to Alternative Technology in the Chlor-Alkali Industry,* United Nations Environment Programme (UNEP) Global Mercury Partnership Chlor-Alkali Area, June 2012 (available at

http://www.unep.org/hazardoussubstances/Portals/9/Mercury/Documents/chloralkali/Partnership%2 0Document%20on%20the%20Conversion%20from%20Mercury%20to%20Alternative%20Technolog y%20in%20the%20Chlor-Alkali%20Industry.pdf)

UNFCCC, 2012 *National greenhouse gas inventory data for the period 1990-2010,* United Nations Framework Convention on Climate Change (UNFCCC), Geneva, Switzerland

Vuuren, D.P. van, Elzen, M.G.J. den, Lucas, P.L., Eickhout, B., Strengers, B.J., Ruijven, B. van, Wonink, S., and Houdt, R. van, 2007 *Stabilising greenhouse gas concentrations at low levels: An assessment of reduction strategies and costs,* Climatic Change, Vol. 81, Issue 2, pp 119-159

Varma, A., Milness, R., Miller, K., Williams, E., de Bruyn, S. and Brinke, L., 2012 *Cumulative Impacts of Energy and Climate Change Policies on Carbon Leakage*, AEA and CE Delft, commissioned by the Department for Business, Innovation and Skills, February 2012

VCI-Prognos, 2012. Background information leading to *Die deutsche chemische Industrie 2030*, Verband der Chemischen Industrie (VCI) and Prognos, Basel, Switzerland, February 2013

Voegele, E., 2011 *BioMCN aims to develop wood-to-methanol plant in Netherlands*, Biodiesel Magazine, May 2011 (available at <u>http://www.biodieselmagazine.com/articles/7820/biomcn-aims-to-develop-wood-to-methanol-plant-in-netherlands</u>)

VNCI, 2012 *De sleutelrol waarmaken, Routekaart Chemie 2012-2030, Energie en Klimaat,* Vereniging van de Nederlandse Chemische Industrie (VNCI), November 2012

Vinyloop, 2012 The VinyLoop process (available at http://www.vinyloop.com/en/)

WEC, 2012 *World Energy Council Energy Efficiency Indicators*, World Energy Council (WEC), (available at <u>http://wec-indicators.enerdata.eu/#/industry-energy-intensity-world-level-trends.html</u>)

Wolf, S., Lambauer, J., Fahl, U., Blesl, M. and Voß, A., 2012 *Industrial heat pumps in Germany – potentials, technological development and application examples,* Institute for Energy Economics and the Rational Use of Energy (IER), Universität Stuttgart, ACHEMA 2012 (available at http://www.ornl.gov/sci/ees/etsd/btric/usnt/03InHPsAchmaIERWolf.pdf)

ZEP, 2011 *The Costs of CO*₂ *Capture, Transport and Storage*, Zero Emission Platform (ZEP), Brussels, Belgium, July 2011

Annex 1: Costs of CCS

Costs of CCS on combustion sources

Stock	Year of assessment	Capture rate ⁶⁸	Cost item	Plant size (Mt CO₂ / year)	Investment costs (2010 € / t CO ₂ annually captured) ⁶⁹	Heat requirements (GJ / t CO ₂ captured)	Electricity ⁷⁰ requirements (GJ / t CO ₂ captured)
Existing (retrofit) and new	2020	85%	Capture and Compression ⁷¹	0.13	1020		
				0.25	714		0.48
				0.5	500		
				1.2	300	3.2	
				3.0	200		
			Transport	All ⁷²	80		
			Storage	All	60		

⁶⁸ Only the emissions of the industrial activity to which capture is applied are taken into account (no emissions from building the capture installation, transporting the fuels, etc.)

⁶⁹ Not annualised (total costs)

 70 For compression (3/4) and fans for pressurising flue gases and circulating solvents (1/4)

⁷¹ Compression is included to pipeline pressure

 72 Investments for transport *do* depend on plant size, however for smaller installations (i.e. <1 Mt CO₂ / year), either combining different emission sources in neighbourhood or limiting transport to several tens of kilometres, yield the indicated investment figure. In case no other emission sources nearby are present and the captured CO₂ needs to be transported over long distances, CCS will not be implemented.

Stock	Year of assessment	Capture rate ⁶⁸	Cost item	Plant size (Mt CO₂ / year)	Investment costs (2010 € / t CO ₂ annually captured) ⁶⁹	Heat requirements (GJ / t CO ₂ captured)	Electricity ⁷⁰ requirements (GJ / t CO ₂ captured)
	2030	85%	Capture and Compression	0.13	612		
				0.25	429		
				0.5	300		1.4673
				1.2	225	0	
				3.0	125		
			Transport	All ⁵	70		
			Storage	All	60		
	2050	95%	Capture and Compression	0.13	327		
				0.25	229		
				0.5	160		
				1.2	130	0	1.13 ⁷⁴
				3.0	90		
			Transport	All ⁵	50		
			Storage	All	60		

 $^{^{\}rm 73}$ For oxyfuel, electricity consumption assumed is 200 kWh/t $\rm CO_2$

⁷⁴ 30% improvement in oxygen production assumed

Costs of CCS on pure sources (process-related emissions)

Stock	Year of assessment	Capture rate ⁷⁵	Cost item	Plant size ⁷⁶ (Mt CO₂ / year)	Investment costs (2010 € / t CO ₂ annually captured) ⁷⁷	Heat requirements (GJ / t CO ₂ captured)	Electricity ⁷⁸ requirements (GJ / t CO ₂ captured)
Existing (retrofit) and new	2020	100%	Capture and Compression ⁷⁹	<0.8	100		
				0.8	40		
				>0.8	30	0	0.4
			Transport	All ⁸⁰	80		
			Storage	All	60		

⁷⁵ Only the emissions of the industrial activity to which capture is applied are taken into account (no emissions from building the capture installation, transporting the fuels, etc.)

⁷⁶ For ammonia, the typical size for the process emissions part is fixed at 0.8 Mt CO2 per annum

⁷⁷ Not annualised (total costs)

⁷⁸ For compression; typically also drying and possibly cleaning is required, consuming electricity (not included here); 10% efficiency improvement assumed to 2030 and another 10% towards 2050

⁷⁹ Compression is included to pipeline pressure

⁸⁰ Investments for transport *do* depend on plant size, however for smaller installations (i.e. <1 Mt CO₂ / year), either combining different emission sources in neighbourhood or limiting transport to several tens of kilometres, yield the indicated investment figure. In case no other emission sources nearby are present and the captured CO₂ needs to be transported over long distances, CCS will not be implemented.

Stock	Year of assessment	Capture rate ⁷⁵	Cost item	Plant size ⁷⁶ (Mt CO₂ / year)	Investment costs (2010 € / t CO ₂ annually captured) ⁷⁷	Heat requirements (GJ / t CO ₂ captured)	Electricity ⁷⁸ requirements (GJ / t CO ₂ captured)
	2030	100%	Capture and Compression	<0.8	100		
				0.8	36		0.36
				>0.8	30	0	
			Transport	All ¹³	70		
			Storage	All	60		
	2050	100%	Capture and Compression	<0.8	100		
				0.8	32		
				>0.8	30	0	0.33
			Transport	All ¹³	50		
			Storage	All	60		

Annex 2: Scenario input parameters

Input parameters of each scenario

Parameter	Year	Continued Fragmentation		Isolated Europe		Differentiated Global Action		Level Playing Field		
	2010	1	5	1	15		15		15	
CO ₂ prices	2020	1	6	2	1	2	6	19		
(2010 € / t CO ₂)	2030	3	3	4	4	54		37		
	2050	5	3	22	21	2	76	19	94	
	2010	(D	(D	()	()	
Delta CO ₂ costs	2020		5	(5		3	()	
(2010 € / t CO ₂)	2030	13		4	4	10		0		
	2050	3	0	221		30		0		
Energy prices		Excl. CO2 costs	Incl. CO2 costs	Excl. CO₂ costs	Incl. CO2 costs	Excl. CO₂ costs	Incl. CO2 costs	Excl. CO2 costs	Incl. CO2 costs	
	2010	21.9	23.1	21.9	23.1	21.9	23.1	21.9	23.1	
Electricity ⁸¹	2020	27.2	28.2	28.0	29.2	28.0	29.4	28.0	29.0	
(2010 € / GJ)	2030	28.2	29.9	35.1	36.7	25.3	26.8	34.2	35.6	
	2050	27.7	29.0	37.6	37.6	26.2	26.2	35.4	35.4	
	2010	7.3	8.2	7.3	8.2	7.3	8.2	7.3	8.2	
Natural gas ⁸²	2020	8.4	9.3	8.4	9.6	8.4	9.8	8.4	9.4	
(2010 € / GJ)	2030	10.1	12.0	10.1	12.6	8.3	11.3	8.3	10.3	
	2050	12.8	15.8	12.8	25.2	6.8	22.3	6.8	17.7	

 $^{^{81}}$ Industry electricity costs with and without CO₂ costs; includes investment costs, interests, fuel costs, wages, transmission and distribution costs, and taxes (but no value added tax for industry)

⁸² Gas prices for use as heat source with and without CO₂ costs; includes transmission and distribution costs and energy taxation

Parameter	Year	Conti Fragme	inued Intation	Isolated	l Europe	Differe Global	ntiated Action	Level Fie	Playing eld			
	2010	11.9	13.0	11.9	13.0	11.9	13.0	11.9	13.0			
Oil ⁸³	2020	12.4	13.5	12.4	13.9	11.8	13.7	11.8	13.2			
(2010 € / GJ)	2030	14.6	17.1	14.6	17.9	11.1	15.1	11.1	13.8			
	2050	17.4	21.3	17.4	33.6	10.0	30.2	10.0	24.2			
	2010	4.9	6.3	4.9	6.3	4.9	6.3	4.9	6.3			
Coal ⁸⁴	2020	5.6	7.1	5.6	7.6	5.2	7.6	5.2	7.0			
(2010€ / GJ)	2030	6.1	9.2	6.1	10.3	5.3	10.4	5.3	8.8			
	2050	6.2	11.2	6.2	27.1	4.7	30.8	4.7	23.0			
	2010	13.2				13.2						
Biomass ⁸⁵	2020	14.3				14.3						
(2010€ / GJ)	2030	14.3				13.3						
	2050		13	3.3		12.3						
	2010		10.0									
Geothermal	2020				7.	.0						
(2010€ / GJ)	2030		5.6									
	2050				5.	.0						
	2010	0.	31			0.	13					
Electricity emission	2020	0.	22			0.	20					
(t CO ₂ / MWh)	2030	0.	18			0.	12					
	2050	0.	09	0.00								

 $^{^{83}}$ Oil prices for use as heat source with and without CO₂ costs; includes transmission and distribution costs and energy taxation

 $^{^{84}}$ Coal prices for use as heat source with and without CO₂ costs; includes transmission and distribution costs, energy taxation and combustion premium for higher CAPEX and OPEX

⁸⁵ Biomass prices for use as heat source; includes transmission and distribution costs and combustion premium for higher CAPEX and OPEX

Annex 3: Fuel mix for heat generation applied to the subsectors

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

Fuel mix for heat generation as applied for the generic subsectors⁸⁶

 $^{^{\}rm 86}$ Excluding bio-based production, which uses 100% biomass for fuel.
Annex 4: Development of energy intensity in the four scenarios

Development of energy (fuel / heat and electricity) intensity for stock towards 2050. The value 1.00 indicates 2010 intensity. Post-built CCS measures and energy effects of biobased feeds are not taken into account.

We assume new stock to have the characteristics of the stock as it would be built at the end of the given intervals (for example, stock built in 2010–2020 has the characteristics of stock that would be built in 2020).

Subsector	Year	Continued Fragmentation					Isolated	l Europe		Differ	entiated	Global	Action	Level Playing Field				
	built	2010	2020	2030	2050	2010	2020	2030	2050	2010	2020	2030	2050	2010	2020	2030	2050	
Other Petrochemicals	<2010	1.00	0.95	0.90	0.80	1.00	0.94	0.88	0.78	1.00	0.92	0.85	0.72	1.00	0.93	0.86	0.74	
	2010-2020		0.69	0.69	0.67		0.69	0.68	0.66		0.67	0.65	0.61		0.68	0.66	0.62	
	2020-2030			0.69	0.67			0.68	0.66			0.65	0.61			0.66	0.62	
	2030-2050				0.67				0.65				0.60				0.62	
Other Basic	<2010	1.00	0.95	0.90	0.80	1.00	0.94	0.88	0.78	1.00	0.92	0.85	0.72	1.00	0.93	0.86	0.74	
	2010-2020		0.69	0.69	0.67		0.69	0.68	0.66		0.67	0.65	0.61		0.68	0.66	0.62	
Inorganics	2020-2030			0.69	0.67			0.68	0.66			0.65	0.61			0.66	0.62	
	2030-2050				0.67				0.65				0.60				0.62	
	<2010	1.00	0.92	0.85	0.72	1.00	0.91	0.83	0.69	1.00	0.88	0.78	0.61	1.00	0.89	0.80	0.64	
Polymers	2010-2020		0.67	0.65	0.61		0.67	0.64	0.59		0.65	0.60	0.52		0.65	0.62	0.54	
	2020-2030			0.65	0.61			0.64	0.59			0.60	0.52			0.61	0.54	
	2030-2050				0.60				0.58				0.51				0.53	

Subsector	Year	Continued Fragmentation					Isolated	l Europe		Differ	entiated	Global	Action	Level Playing Field				
	built	2010	2020	2030	2050	2010	2020	2030	2050	2010	2020	2030	2050	2010	2020	2030	2050	
Specialty Chemicals	<2010	1.00	0.79	0.62	0.39	1.00	0.76	0.58	0.35	1.00	0.69	0.48	0.24	1.00	0.71	0.51	0.27	
	2010-2020		0.58	0.49	0.35		0.56	0.46	0.31		0.51	0.39	0.22		0.53	0.41	0.25	
	2020-2030			0.48	0.34			0.45	0.30			0.38	0.22			0.40	0.24	
	2030-2050				0.33				0.29				0.20				0.23	
Consumer Chemicals	<2010	1.00	0.78	0.62	0.39	1.00	0.76	0.58	0.34	1.00	0.69	0.48	0.24	1.00	0.71	0.51	0.27	
	2010-2020		0.58	0.49	0.35		0.56	0.46	0.31		0.51	0.39	0.22		0.53	0.41	0.25	
	2020-2030			0.48	0.34			0.45	0.30			0.38	0.22			0.40	0.24	
	2030-2050				0.33				0.29				0.20				0.23	

Product group	Techno-	Year stock	Continued Fragmentation				Isolated Europe				Differe	entiated	Global	Action	Level Playing Field				
	logy	is built	2010	2020	2030	2050	2010	2020	2030	2050	2010	2020	2030	2050	2010	2020	2030	2050	
Ammonia 87	(Current)	<2010	1.00	0.90	0.81	0.81	1.00	0.90	0.81	0.81	1.00	0.90	0.81	0.81	1.00	0.90	0.81	0.81	
	Steam	2010-2020		0.57	0.55	0.51		0.57	0.55	0.50		0.57	0.54	0.47		0.57	0.54	0.48	
	reforming	2020-2030			0.52	0.48			0.52	0.47			0.50	0.44			0.51	0.45	
	(baseline)	2030-2050				0.48				0.46				0.43				0.44	
	SMR with CCS	2020-2030			0.55	0.50			0.54	0.49			0.52	0.46			0.53	0.47	
		2030-2050				0.50				0.51				0.47				0.48	
	(Current)	<2010	1.00	0.93	0.86	0.77	1.00	0.91	0.83	0.72	1.00	0.90	0.79	0.66	1.00	0.91	0.81	0.69	
	Naphtha	2010-2020		0.61	0.59	0.55		0.61	0.59	0.54		0.61	0.58	0.52		0.61	0.58	0.53	
	steam cracking	2020-2030			0.57	0.53			0.56	0.52			0.54	0.49			0.55	0.50	
Cracker	(baseline)	2030-2050				0.52				0.51				0.48				0.49	
Cracker products	Naphtha steam cracking with CCS	2030-2050								0.55				0.51				0.52	
	Ethanol-to- ethylene	2030-2050								0.26				0.26				0.26	

⁸⁷ As is stated above, these numbers only reflect fuel / heat and electricity use and exclude feedstock use, analogous to Figure 7-13

Product group	Techno-	Year stock is built	Continued Fragmentation					Isolated	l Europe	à	Differe	entiated	Global	Action	Level Playing Field			
	logy		2010	2020	2030	2050	2010	2020	2030	2050	2010	2020	2030	2050	2010	2020	2030	2050
	(Current)	<2010	1.00	0.98	0.97	0.97	1.00	0.98	0.97	0.95	1.00	0.98	0.97	0.96	1.00	0.98	0.97	0.96
	Membrane cell <i>(baseline)</i>	2010-2020		0.87	0.86	0.85		0.87	0.86	0.84		0.87	0.86	0.84		0.87	0.86	0.84
		2020-2030			0.86	0.84			0.86	0.84			0.85	0.83			0.85	0.83
		2030-2050				0.84				0.83				0.82				0.82
Chlor Alkalis	Oxygen	2010-2020						0.83	0.82	0.81						0.83	0.82	0.80
	Cathode	2020-2030															0.82	0.80
	electrolysis ⁸⁸	2030-2050																
	ODC with	2020-2030											0.82	0.80			0.82	0.80
	CCS ⁸⁸	2030-2050												0.79				0.80

⁸⁸ Energy and fuel use of compensating production of hydrogen in case of ODC are included in this figure. Associated feedstock use is not.

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Cefic aisbl Avenue E. Van Nieuwenhuyse 4 B - 1160 Brussels Belgium Tel: +32 2 676 72 11 Fax: +32 2 676 73 00 mail@cefic.be www.cefic.org

