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Exploring the limits for CO_2 emission abatement in the EU power and industry sectors - Awaiting a breakthrough

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Abstract

We assessed the prospects for presently available abatement technologies to achieve significant reductions in CO_2 emissions from large stationary sources of CO_2 in the EU up to Year 2050. This study covers power generation, petroleum refining, iron and steel, and cement production. By simulating capital stock turnover, scenarios that assume future developments in the technology stock, energy intensities, fuel and production mixes, and the resulting CO_2 emissions were generated for each sector. The results confirm that the EU goal for reductions in Greenhouse Gas Emission in the sectors covered by the EU Emission Trading System, i.e., 21% reduction by 2020 as compared to the levels in 2005, is attainable with the abatement measures that are already available. However, despite the optimism regarding the potential for, and implementation of, available abatement strategies within current production processes, our results indicate that the power and industrial sectors will fail to comply with more stringent reduction targets in both the medium term (2030) and long term (2050). Deliberate exclusion from the analysis of mitigation technologies that are still in the early phases of development (e.g., CO_2 capture and storage)

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provides an indirect measure of the requirements for novel low-carbon technologies and production processes.

Keywords: Scenarios, CO_2, EU.

1 Introduction

In February 2011, the European Council reconfirmed the EU objective of reducing greenhouse gas (GHG) emissions by 80%–95% by 2050, as compared to levels in 1990 (European Commission, 2011a). To achieve these emission reductions, it is clear that all sectors of the economy will have to make major contributions. In recent years, a wide range of low-carbon scenarios, roadmaps, and pathways have been developed by academic groups (Schade et al., 2009; Pathways, 2011; EWI, 2011), businesses (Eurelectric, 2010; Europia, 2011; PWC, 2012), governmental agencies (European Commission, 2011b) and NGOs (SEI, 2009; ECF, 2010; Greenpeace/EREC, 2010), to explore how transition to a low-carbon economy could be realized. The resulting array of scenarios effectively illustrates the normative nature of the scenario analysis approach. Although the scope, underlying assumptions, and conclusions vary considerably across the different investigations, the general message is that in the presence of a strong, consistent policy framework, GHG emissions in the EU could be significantly reduced over the coming decades. While the relative importance assigned to specific mitigation technologies and practices varies, most studies have emphasized the significance of technical change for the transformation process, which will involve a massive shift away from fossil fuels towards low-carbon production processes.

In most of the above-mentioned studies the focus has been on the transformation of the power sector, and the analyses have typically involved speculation regarding the long-term potential for, and performance of, technologies that are in very different phases of development, from well-established technologies to technologies still in the research and demonstration phases. Several of the technologies that presumably will contribute most to CO_2 emission reductions between now and 2050 are in the latter category.

That most studies focus on the power sector is logical, since there are many options available for reducing CO_2 emissions from this sector emission levels must be reduced to close to zero leading up to Year 2050 (European Commission, 2011b). However, there is a need to extend the scope to other large stationary sources of CO_2. In the power sector, there is a relatively broad mix of generation technologies that could replace existing fossil-fueled capacities. In addition, Carbon Capture and Storage (CCS) could be used, assuming the timely and successful commercialization of CCS. In the industrial sectors, production is typically dominated by a limited number of production processes. Thus, the options to reduce CO_2 emissions are fewer and tends to be less-developed than those for the power sector.

Many of the power plants and industries that are currently in operation were commissioned in the period from 1960 to 1980. Thus, a large share of the existing capital stock will need to undergo major refurbishments or be replaced within the coming decades. The critical questions as to when, how fast, and to what extent new low-carbon technologies can penetrate these sectors need to be addressed. The common practice, which entails the inclusion in the transformation process of both established and emerging technologies in analyses of the roles of new low-carbon technologies, is reasonable. With a time horizon of 40 years, significant technological progress is possible and indeed likely. However, there are significant uncertainties surrounding the assumptions related to the timing of the possible introduction and the extent to which new low-carbon technologies can penetrate the different sectors.

To understand better the challenges associated with the transition towards lowered CO_2 emissions, there is a need to explore further the possibilities and limitations imposed by the current industrial structure. In this paper, we assess how the prospects for future CO_2 emission reductions vary across four key sectors. Rather than addressing the issue of the prospects of new low-carbon technologies, we instead focus on exploring the limits for CO_2 abatement within current production processes. However, by comparing the emission scenarios with indicative emission trajectories for the period 2010–2050, we provide an indirect measure of the requirement for new low-carbon technologies and industrial production processes.

2 Methodology

A scenario analysis was applied to assess the prospects for CO_2 emission abatement in the four major CO_2-emitting activities of the EU stationary sector. The analysis covered power generation, petroleum refining, iron and steel production, and cement manufacturing in the EU-27 countries and Norway. By exploring factors relevant to future CO_2 emissions in each sector, such as activity level, the expected pace of capital stock turnover, structural changes, deployment of available abatement options, and market trends, emission levels trajectories for the period 2010–2050 were derived for each activity. In total, six scenarios were analyzed: three scenarios for the future development of the power sector (each of which describes a different future with respect to technology and fuel mixes), and one scenario each for the remaining industrial sectors describing the future development of the production mix for each sector.

Scenario analysis in the context of GHG abatement typically involves speculation as to the long-term potential and performance of technologies in very different phases of development, ranging from well-established technologies to technologies that are still in the research and demonstration phases. In the present study, by disregarding assumptions related to the potential and performance of mitigation technologies that are not yet commercially available but that are assumed to significantly contribute to CO_2 emission reductions between now and 2050, we provide an indirect measure of the requirements for new low-carbon technologies and industrial production processes. For the power sector, this means that that CCS is not included as an alternative and that assumptions as to new capacity additions are limited to the period up to Year 2020 (thereafter, the expected capacity shortage is defined as the difference between generation from the capacities available in the year 2020 and an assumed demand). This approach sidesteps the question of the relatively long-term potential of low-carbon generation technologies, while capturing the magnitude of the required capacity expansion. Thus, for the industrial sectors, CCS is not included as an alternative and radically new iron and steel and cement production processes are not considered (for a review of potential breakthrough technologies in the iron and steel and cement industry, see Croezen and Korteland, 2010).

The sectors covered in the present study exhibit different characteristics in terms of production processes applied, industry structure, and available abatement options. Therefore, the methodological approach used differs depending on the branch-specific conditions. The general methodological approach involves:

1) A thorough description and characterization of the current industry structure.
2) Assessment of the key factors and trends relevant to future CO_2 emissions in each industry.
3) Scenario analysis. By simulating capital stock turnover, scenarios have been generated for each sector that incorporate changes in technology stock, energy intensities, fuel and production mixes, and the resulting development of CO_2 emissions. A detailed description of the scenario generation approach is given in *Section 2.2*.
4) Impact analysis from the scenario outcomes with respect to the reductions in emissions achieved in each sector.

2.1 *Description of the key characteristics of the industries*

An important element of the analysis was to consider how age structure, fuel mix, activity levels, demand structure, and the types of production processes applied contribute to facilitating or hindering the shift towards less-emission-intensive production. The current status of each branch is described based on information obtained from the Chalmers Power Plant Database (Kjärstad and Johnsson, 2007) and the Chalmers Industry Database (Rootzén et al, 2011). These databases include facility-level data on key processes and plant components related to energy use and CO_2 emissions, and they provide CO_2 emission data at the installation level (2005–2010), as well as allocated emission allowances (2005–2012).

Table 1 outlines the scope of the databases and the various data sources used to construct them.

Table 1. Components of the Chalmers databases applied in the current analysis.

	Scope
Power plants	- Almost full coverage of grid-connected power plants with net capacity >10 MW in EU-27 countries, Norway, and Switzerland. - Data regarding age, fuel, capacity, technology, and present status registered down to block level (see Kjärstad and Johnsson (2007) and references therein).
Petroleum refineries	- Includes 114 petroleum refineries from 22 EU-27 countries. - Classification of refineries according to configuration/complexity - Includes installation-level information on crude input, main process equipment, and process capacities for this equipment (Johansson et al., 2011; Oil and Gas Journal, 2007). - Information on age structure, defined by the year of commissioning of each refinery (European Commission, 2010b).
Iron and steel production facilities	- Includes 36 integrated steel plants (85 blast furnaces [BF] and 102 basic oxygen furnaces [BOF]) and 222 electrical arc furnaces (EAF), operating in EU-27 (Steel Institute VDEh, 2009) - Details of production routes and production capacities - Information on age structure of the capital stock, defined by the year of commissioning of the BF or EAF (Steel Institute VDEh, 2009)
Cement manufacturing	- Includes 250 cement plants with 406 cement kilns (Cembureau, 2001; GCD, 2009) - Includes installation-level information on kiln-types (including pre-heaters and pre-calciners), main fuel, and production capacities (Cembureau, 2001; GCD, 2009). - Information on age structure of the capital stock, defined by the year of commissioning of the cement kilns (Cembureau, 2001; GCD, 2009).

To structure the analysis, the following five general categories of characteristics and trends were considered to be important for the description of the current status of each branch in the context of future prospects for CO_2 abatement:

- **Age structure.** The pace of capital stock turnover is crucial to the rate at which low-carbon technologies can be expected to penetrate the sectors (Worrell, 2005; IEA, 2007).Thus, the age structure of the current capital stock provides an indication of the expected pace of replacement of emission-intensive production technologies.
- **Activity level.** Recent trends in demand and production have been utilized in the present study to provide a point of departure and references for assumptions regarding future activity levels. Nevertheless, the decision as to how to represent the future evolution of demand and production levels is not trivial. The unfolding of the financial crisis in 2008–2009 and the effects of the current economic crisis on industrial production and power demand clearly illustrate the challenges associated with any attempt to capture long-range features of the economy.
- **Structure of production.** Electricity generation, petroleum refining, and the manufacture of iron and steel and cement involve an array of technologies and production processes. We have briefly outlined the production processes and technologies that currently predominate in each branch. In the power sector, a relatively broad mix of generation technologies is employed. In the industrial sectors, while the specific setups of the production processes may vary, production is typically dominated by a limited number of general production technologies.

- **Market characteristics**. Economic considerations are not explicitly part of the analysis. However, a general understanding of the functioning of the strategic markets, both upstream and downstream, in each branch is essential for understanding the industry as a whole.
- **Fuel mix.** Fossil fuel combustion accounts for the greatest share of CO_2 emission in this study. The share and importance of fossil fuels in the energy mixes gives an indication of the prospects for achieving future reductions in CO_2 emissions through fuel switching. A continued shift towards less-carbon-intensive fuels is assumed to take place, to various degrees, in all sectors during the studied time period.

All the data used to describe the current status have been compiled and aggregated for the EU-27 countries and Norway. Table 2 summarizes the most important characteristics and trends that form the basis for the scenario analysis.

Table 2. Key characteristics and trends relevant to future levels of CO_2 emissions in each branch of industry.

	Key characteristics and trends
Power generation	*Age structure*. The age structure varies across the different technologies and fuel classes. While more than 80% of the installed capacity of the oil-, coal-, and lignite-fired thermal power plants were commissioned before 1990, most of the installed capacities of natural gas-fired power plants and wind turbines were commissioned over the past two decades. *Activity level*. Electricity demand has increased considerably over the last two decades. Average annual gross electricity generation in the EU-27 and Norway in the period 2005–2010 was approximately 3450 TWh/yr, up from 2700 TWh/yr in 1990 (Eurostat, 2011). *Structure of production*. Conventional thermal power plants (mainly fossil-fueled) dominate the EU power sector both in terms of installed capacity (~58%) and share of electricity generation (~55%), followed by nuclear and hydro power plants

	and "new" renewables (mainly wind, solar, and biomass). The clearest trends have been in the rapid expansion of the installed capacity of natural gas-fired power plants and the use of renewables (i.e., biomass, on-shore wind power and solar photovoltaics [PV]).
	Market characteristics. Although the long-term goal is an integrated European electricity market, the balancing of supply and demand remains a national (and in some cases, regional) concern. The current level of cross-border trade is modest, due largely to constraints on the capacities of existing interconnections (CEEPR, 2005).
	Fuel mix. Fossil fuel-fed power plants still account for more than half of the electricity supply in the EU-27 countries (coal, ~30%; gas, ~20%; and oil, ~3%). The two most noteworthy trends over the last two decades have been: 1) a sharp increase in the use of natural gas (replacing coal and oil) for power production; and 2) an increase in average thermal efficiency, as driven by the replacement of old, inefficient plants (EEA, 2011).
Petroleum refining	*Age structure*. More than 90% of European refineries were commissioned before 1980 (European Commission, 2010). Typically, these refineries were originally optimized to maximize the output of gasoline and fuel oil (UKPIA, 2006). Most investments over the past decades have been directed towards refurbishment of existing process units and expansion of the conversion and treatment capacities.
	Activity level. The total output of petroleum products from EU refineries has increased slightly, from 687 Mtoe/yr in 1990 to an average of 730 Mtoe/yr in the period 2005–2010 (Eurostat, 2011). Due to changes in the fuel demand and quality specifications, process intensity has increased noticeably and consequently, both energy consumption and associated CO_2 emissions have increased. The demand for heavy fuel oil has decreased steadily, while the demand for transport fuels has increased. Within the transport fuel segment, the market for middle distillates (i.e., diesel and aviation fuel) has expanded at the expense of lighter distillates (i.e., gasoline) (Concawe, 2008; Purvin and Gertz, 2011).
	Structure of production. Refineries are complex industrial plants that convert crude oil into a wide range of products. EU refineries range in size and complexity from small topping and specialty refineries to high-conversion cracking refineries (European Commission, 2009a). While all the refineries undertake crude oil distillation, the specific configuration of further processing varies among individual refineries, depending on the crude diet being processed and how the product mix is

	optimized (Johansson et al., 2011). *Market characteristics.* Upstream, EU refineries import crude oil from several regions, with the bulk of oil imports originating in the North Sea, North Africa, and Russia (Concawe, 2008). Downstream, EU refineries typically supply national or regional markets. While EU refineries have been struggling to adapt to changes in domestic demand trends, the demand-supply imbalance has been compensated for through imports of diesel from the CIS region and exports of gasoline to the USA (Purvin and Gertz, 2011). *Fuel mix.* Most refineries have been designed to utilize a mixture of internally derived fuels. The furnaces and boilers that feed the different sub-processes are typically fueled by a combination of refinery gas, residual fuel oil, and other residual petroleum fuels. In recent years, there has been an increase in the incorporation of imported natural gas into the refinery fuel mix.
Iron and steel production	*Age structure.* The age structures of the two major steel production routes differ considerably. Whereas more than 80% of the blast furnaces currently in operation in the EU were commissioned before 1980, most of the EAF currently in service were commissioned after 1980. *Activity level.* Average annual steel production for the period 2005–2010 was approximately 189 Mt crude steel/yr. With the exception of 2009, when production was down to 139 Mt crude steel/yr, annual production has been in the range of 172–210 Mt crude steel/yr (Eurofer, 2011). Even though the European share of the world steel market has gradually declined, the EU remains the second largest steel-producing region in the world. *Structure of production.* Although the iron and steel industry has a complex industrial structure, two production routes dominate EU production (European Commission, 2009b): - Integrated steel plants involve a series of interconnected production units (coking ovens, sinter plants, palletizing plants, BF, BOF and continuous casting units), which process iron ore and scrap metal to crude steel. - Mini-mills, in which scrap metal, direct reduced iron, and cast iron are processed in EAF to produce crude steel. While primary steelmaking (integrated route) dominates EU production, the secondary steelmaking route (mini-mills) has gradually gained market share (Eurostat, 2002; WSA, 2011). *Market characteristics.* The major inputs of iron ore, scrap metal, and coking coal, and the outputs of crude steel in different forms are all global commodities. However, the market conditions in the respective sub-markets vary. Whereas for iron ore and coke

	the EU steel industry largely depends on imports, scrap steel is typically supplied domestically (Ecofys, 2009a). Downstream, primary steel (BF/BOF) accounts for approximately 58% and secondary steel 42% of the total output of crude steel in the EU-27 and Norway. As primary and secondary crude steel (EAF) differ with respect to quality, they are not perfect substitutes (Ecofys, 2009a). Secondary steel does not meet the requirements of the high-quality segments of the market. *Fuel mix*. Coke, pet-coke, and oil dominate the energy mix in the integrated steelmaking route. Coke functions both as a fuel and as a reducing agent in the blast furnace. Electricity constitutes the primary energy input in secondary steelmaking.
Cement manufacturing	*Age structure*. More than 70% of the cement kilns in EU-27 were commissioned before 1980. The general trend for the industry after 1980 has been towards dry manufacturing processes. Thus, most of the plants that were commissioned in the period 1981–2010 apply dry process rotary kilns with pre-heaters and pre-calciners (GCD, 2009; Moya et al., 2011) *Activity level*. The annual production of cement in EU- 27 has remained in the range of 190–270 Mt cement/yr over the last decade (Cembureau, 2011). *Structure of production*. Currently, there are 268 cement plants in the EU-27 countries (of which 250 are listed in the Chalmers IN db), with 377 kilns. Production capacities range from a couple of hundred tons to several thousand metric tons cement per day. Dry process kilns account for approximately 90% of European cement production. The remainder is produced in semi-dry or semi-wet process kilns (7.5%) and in wet process kilns (2.5%) (European Commission, 2010). *Market characteristics*. Cement is a bulky material and trade has typically been confined to national or regional markets. Imports to and exports from the EU have so far been relatively limited, and concerns have been raised about competition from cement producers located in countries that lack carbon constraints, i.e., counties of North Africa. *Fuel mix*. Although the share of alternative fuels has increased, fossil fuels (typically, pet-coke and coal) still dominate the energy mix in the majority of cement plants in the EU.

2.2 Scenario generation approach and assumptions

As mentioned above, the current analysis is restricted to the technical potentials of available abatement options and thus, it largely ignores possible economical and institutional constraints. As a radical reduction in the levels of CO_2 emission is the principal objective in all the scenarios, other environmental aspects are not included in the present study. Figure 1 presents the general structure of the scenario generation approach. While some abatement strategies are applicable to all branches, i.e., fuel switching and energy efficiency improvements, the specific scenario setup varies for the individual branches. The individual scenarios have been generated based on branch- and technology-specific parameters and boundary conditions. Scenario inputs have been chosen to reflect a development in which ambitious measures are taken to *exploit the abatement strategies currently available in each sector*.

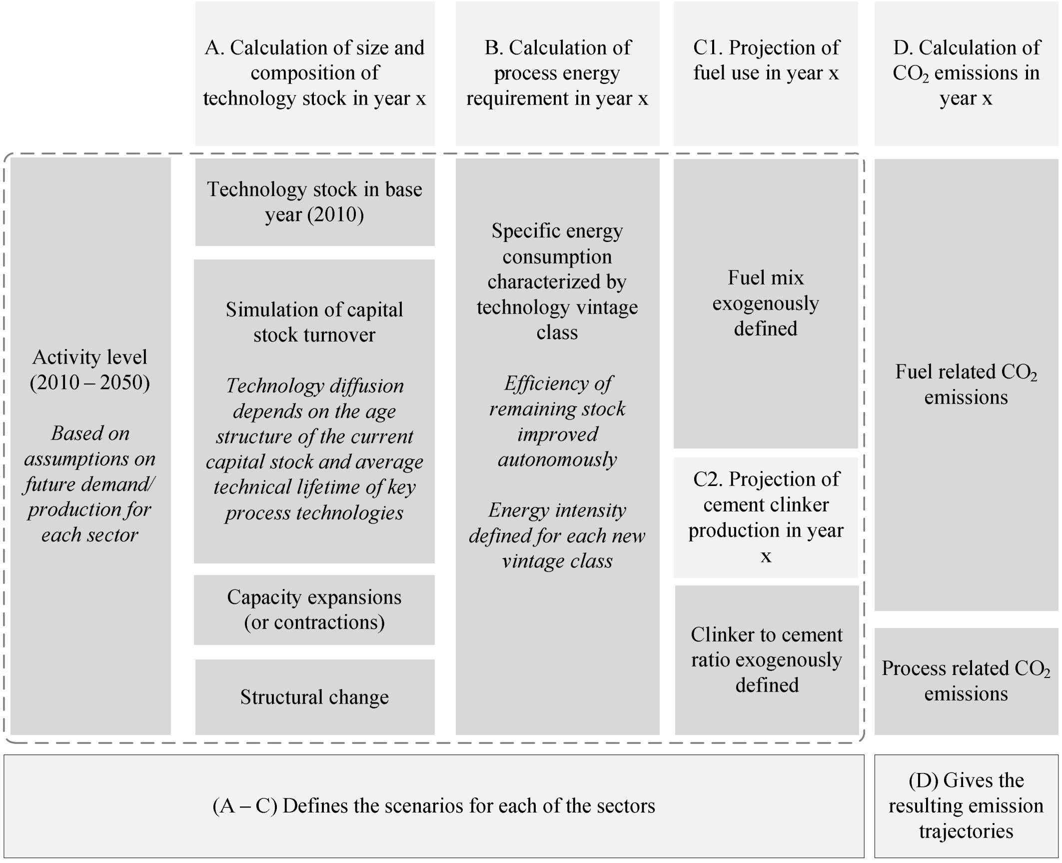

Figure 1. General structure of the scenario analysis approach. Capital stock turnover, expansions or reductions of capacity, and structural changes result in changes in the size and composition of the technology stock (A). The decommissioning of old capital, the introduction of state-of-the-art production processes, and gradual improvement in the efficiency of the remaining current capital stock reduce process energy requirements (B). Shifts towards less-carbon-intensive fuels contribute to reducing specific emissions (C1). For the cement industry, increased use of clinker substitutes contribute to reducing both fuel- and process-related CO_2 emissions (C2). The combined effects of A – C1, C2 as well as the assumptions made regarding the activity level in each year, give the annual CO_2 emissions (D).

A key parameter governing future activity levels and CO_2 emissions is the evolution of demand. With a time horizon of 40 years, any assumptions as to future demand levels are subjective. Here, future activity levels have been exogenously defined based on a number of basic assumptions. The development of electricity demand, taken from EWI (2011), is chosen to reflect a development with relatively moderate growth rates (Greenpeace, 2010; Delarue et al, 2011; European Commission, 2011b). Electricity demand in the EU-27 countries and Norway is assumed to increase from

3250 TWh to 4250 TWh in the period 2010–2050 (herein denoted as the *Reference demand*). Demand growth, primarily driven by the shift from fossil fuels to electricity, in key end-use sectors (such as the transport, residential, and industrial sectors) is assumed to override the effects of improvements in end-use efficiency. Accordingly, electrification of the transport sector and reduced demand for petroleum products in other end-use sectors are assumed to lead to an overall reduction in demand from 684 Mtoe in 2010 to 290 Mtoe in 2050 (Europia, 2011; European Commission, 2011b). No major changes in the overall demands for crude steel and cement are assumed. Total steel production is assumed to increase from 170 Mt steel/yr in 2010 to 200 Mt steel/yr (comparable to the production levels prior to the current economic crisis) and thereafter remain constant throughout the studied period. Correspondingly, cement production is assumed to increase from 190 Mt/yr in 2010 to 240 Mt/yr in 2020 and remain constant thereafter.

Table 3 lists the exogenously defined parameter values, which describe future activity levels and emission caps. As a reference, the emission trajectories that result from each of the scenarios have been compared with indicative emissions caps for each branch. The emissions trajectories that define the emissions caps for the period 2010–2050 have been derived based on the emission cap for the EU ETS for the period 2010–2020 and the proposed reduction targets for 2050, for the period beyond 2020 (as outlined in the European Commission's "Low-carbon economy roadmap"; European Commission, 2011b). This gives an assumed reduction in emissions of 95% for the power sector and 85% for the three industrial sectors investigated with the reference year of 2010 (Table 3) The generous cap set for the period 2010–2020 for the industrial sectors reflects a development in which the sectors that are exposed to the risk of carbon leakage continue to receive a significant share of their emission allowances for free, and in which surplus allowances are carried over from Phase II to Phase III of the trading scheme.

Table 3. Exogenously defined parameter values, describing future activity levels and emission caps. All values are expressed relative to the values for Year 2010.

		2010	2020	2030	2050
Power generation	Activity level[a]	1	1.14	1.22	1.31[b]
	Emission cap	1	0.77	0.48	0.05
Petroleum refineries	Activity level[c]	1	0.91	0.80	0.42
	Emission cap	1	0.97	0.59	0.14
Iron and steel manufacturing	Activity level	1	1.16	1.16	1.16
	Emission cap	1	0.97	0.59	0.14
Cement manufacturing	Activity level	1	1.26	1.26	1.26
	Emission cap	1	0.97	0.59	0.14

[a] The same Reference demand has been applied in all three scenarios for the power sector.

[b] Note that the projections for EU electricity demand in the period 2010–2050 vary significantly. In 2050, electricity demand in the Greenpeace Energy Revolution scenario is 3730 TWh, while in the European Commission's Effective Technology Scenario demand is estimated at 5800 TWh for the same year. (Greenpeace, 2010; Delarue et al, 2011; European Commission, 2011b). The demand projection used here is in the lower range of the demand growth forecasts.

[c] Assuming a decline in demand in all end-use sectors throughout the studied period and a drastic reduction in demand in the transport sector after 2030 (Europia, 2011; European Commission, 2011b).

A common feature of all of the branches assessed herein is an ageing capital stock that is heavily dependent upon the use of fossil fuels. Thus, a large share of the existing capital stock will need to undergo major refurbishment or replacement over the coming decades. Based on the age structure of the existing capital stock, as illustrated in Figures 2 and 3, and assumptions made as to the average technical lifetime of key process technologies, we simulated capital stock turnover up to 2050 for each branch. The assumption is that capital stock is retired as soon as it reaches the end of its technical lifetime. Possible capacity shortages are assumed to be covered by investments in new production capacities. In the iron and steel and the cement industries, retired production capacity is replaced with new production capacity in line with the dominating technological designs, albeit with improved performances in terms energy efficiency and CO_2 intensity (technological options that are based on processes different from the existing processes have not been considered). In the refining industry, new investments are assumed to be in desulfurization units or advanced conversion units; no new investments in primary refining capacity take place. For the power sector, retired low-carbon capacities (i.e., nuclear and renewable) are assumed to be replaced with similar generation technologies. The stringent emissions cap limits the opportunity for new fossil-fueled capacity. However, to assess the long-term effects of different strategies to meet the expected remaining capacity shortage up to 2020, we explore two scenarios in which new fossil-fueled capacity are allowed.

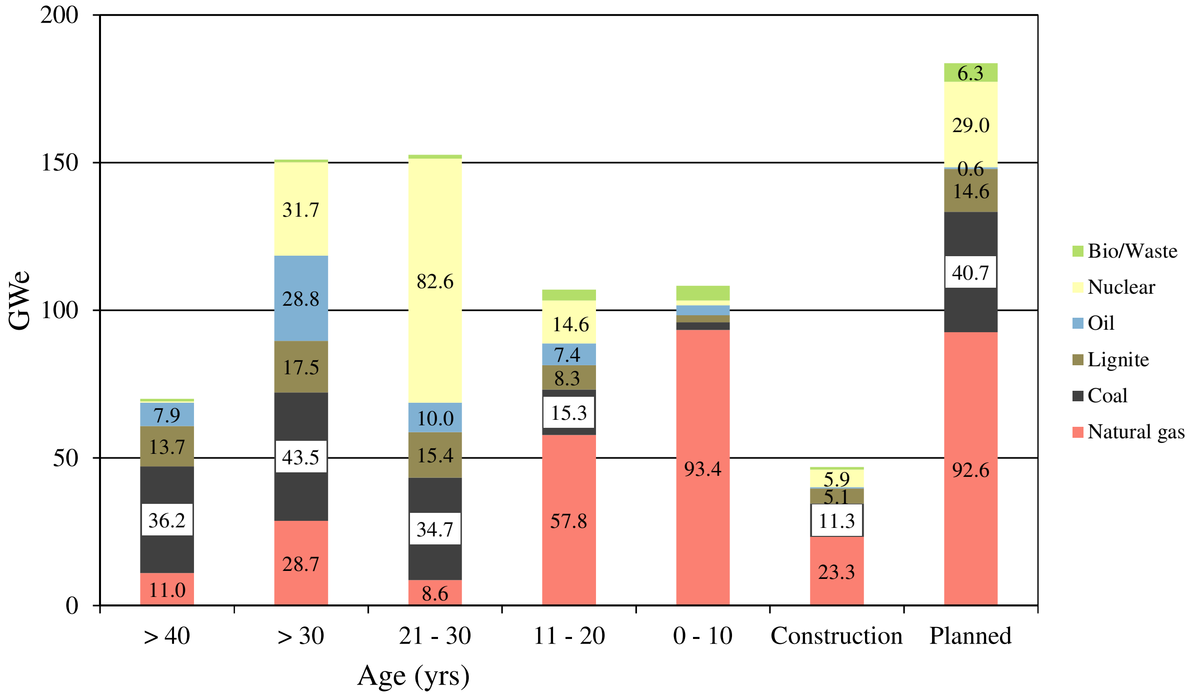

Figure 2. Net capacities of thermal power plants in the EU-27 and Norway, distributed by fuel used and plant age. Source: Chalmers Power Plant Database (Kjärstad and Johnsson, 2007), March 2011.

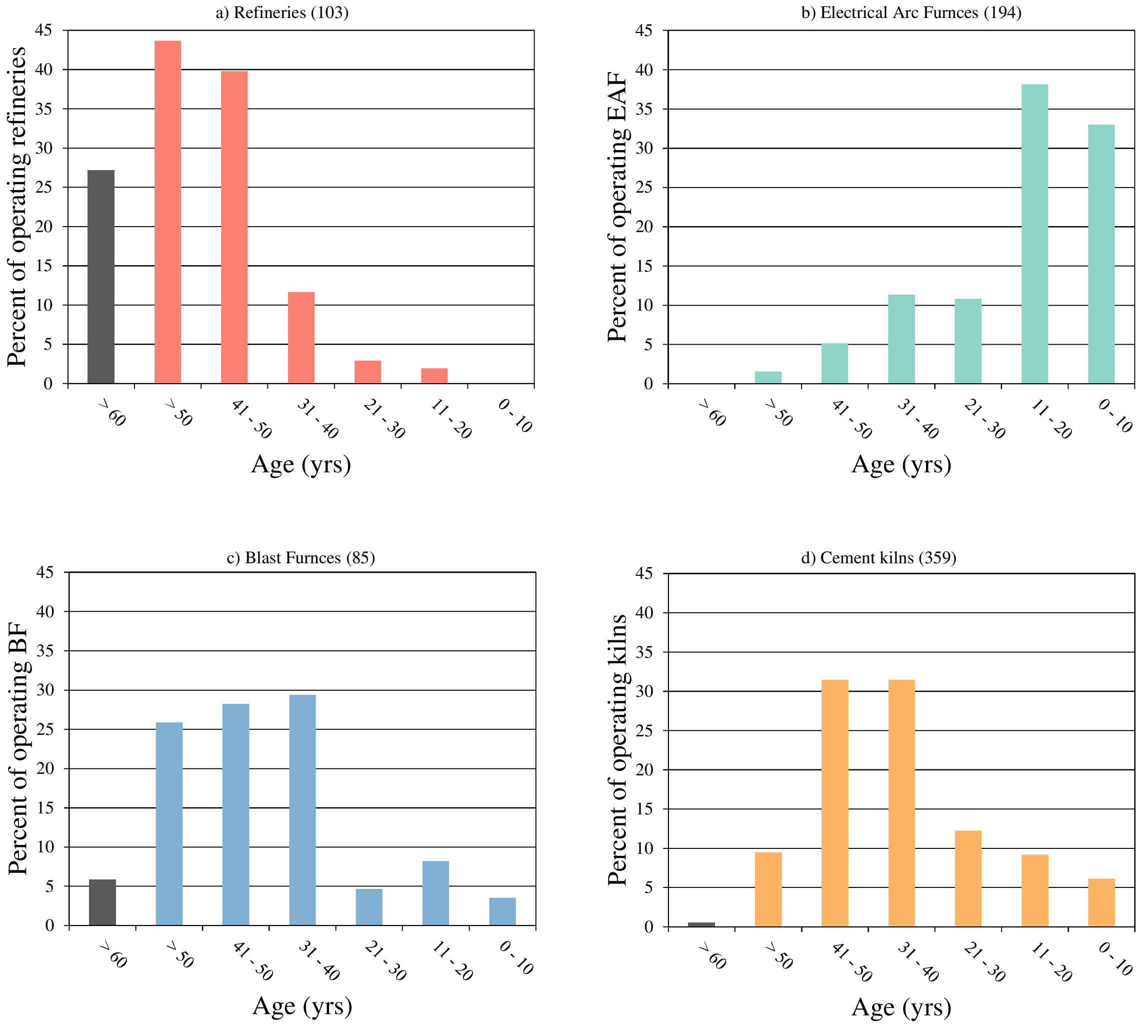

Figure 3. Age structures of petroleum refineries, iron and steel and cement industries in the EU-27 and Norway. a) The percentages of operating refineries commissioned in each decade; 98 of the 103 refineries were commissioned before 1980 (European Commission, 2010). b–c) The percentages of operating BF and EAF commissioned in each decade; 71 of the 85 BF were commissioned before 1980, while 161 of the 194 EAF were built after 1980 (Steel Institute VDEh, 2009). d) The percentages of operating cement kilns commissioned in each decade; 260 of the 359 cement kilns were commissioned before 1980 (Cembureau, 2001; GCD, 2009).

2.3 Branch-specific scenario attributes

The assessed branches have various starting points and capabilities to deal with the challenges associated with CO_2 emission reductions. Consequently, the scenario generation approach has been adapted to reflect the conditions in the respective branches.

2.3.1 Power sector

The challenges associated with transforming the EU power sector have been thoroughly explored in the literature (e.g., Schade et al., 2009; Odenberger and Johnsson, 2010; EWI, 2011). The power sector differs in many respects from the industrial sectors. Perhaps most important for the power sector with respect to the prospects for radical reductions in CO_2 emissions is the technological heterogeneity and the relatively high number of alternative generation technologies. Thus, we refined the problem statement to highlight three crucial factors: (1) the phase-out pattern of the existing capital stock; (2) the limitation for new (albeit conventional, e.g., without CCS) fossil generation capacity given stringent emissions reduction targets; and (3) the magnitude of the required expansion of capacity for low-carbon power generation technologies. These three factors have been explored in a back-casting exercise to assess three scenarios for the future development of the European electricity supply system. The assumed increase in electricity demand (I) in combination with the gradual retirement of existing capacities (II) creates a deficit in generation capacity, which will have to be met by investments in new capacities (III). The following basic assumptions apply to all the scenarios:

(I) *Electricity demand.* The Reference demand specified in Table 3 is used as a benchmark when estimating the capacity expansions required to balance supply and demand in the period 2010–2050. This assumes that electricity demand will grow linearly from 3250 TWh in 2010 to 4250 TWh in 2050 in all the scenarios. This growth rate corresponds approximately to the projected growth rate in OECD Europe in the IEA ETP Blue Map scenario (IEA ETP, 2010), although it is moderate compared to other demand growth scenarios (cf. Greenpeace, 2010; Delarue et al, 2011; European Commission, 2011b).

(II) *Phase-out of existing capacities*. The phase-out pattern of the existing capital stock is based on the age structure of the plants (Fig. 2) and assumes that each plant will be retired when it has reached the end of its technical lifetime. The phase-out pattern is assumed to be the same in all the scenarios.

(III) *New capacities*. Assumptions regarding investments in capacity additions are limited to the period up to 2020. Beyond 2020, aside from nuclear and RES reinvestments, no new investments are made. This is so as to capture the long-term effects of near-term decisions, while avoiding the question of the long-term potentials of new low-carbon technologies.

Table 4 summarizes the assumptions made regarding the technical performance of the generation technologies included in the analysis.

Table 4. Technical characteristics and fuel emission factors. The same assumptions are applied to all three scenarios.

Generation technology	Average technical lifetime[a] (years)	Average load factor[b] (%)	Average net electric efficiency[c] (%)	Fuel emission factor (tCO_2/GJ)[d]
Thermal power plants:				
Coal	40	54–59	38–48	0.095
Lignite	40	54–59	38–43	0.110
Oil	40	20–30	44–46	0.074
Peat	40	59	30–31	0.106
Waste	40	57–60	30–31	0.050
Biomass	40	57–60		
Natural gas CCGT	25	45	48–51	0.057
Nuclear	60	80–84	-	-
Hydro	75	30–37	-	-
Wind			-	-
Onshore	25	19–23		
Offshore	25	20–34		
Solar			-	-
PV	25	9–11		
Thermal (CSP)	25	22–34		
Geothermal	40	30	-	-
Other RES (tide, wave)	25	29	-	-

[a] Assumptions as to the technical lifetimes of the various generation technologies are based on previous studies (Odenberger and Johnsson, 2010; EWI, 2011; Tzimas et al., 2009).

[b] Estimated based on previous data (European Commission, 2010c; ECN, 2011; EEA, 2011; Eurostat, 2011a).

[c] The low-end estimates represent the average net efficiencies of existing capacities for natural gas-, coal-, lignite-, and oil-based plants(Graus and Worrell, 2009), as well as biomass-, peat-, and waste-based plants (European Commission, 2009). The high-end estimates represent the average net efficiencies of new capacities (Tzimas et al., 2009; Graus and Worrell, 2009; Eurelectric, 2011). The efficiency levels of nuclear and renewable generation technologies are not given, as they are not required for calculations of CO_2 emissions.

[d] Estimated based on previous studies (EEA, 2006; Graus and Worrell, 2009; Obermoser et al. 2009).

To assess the prospects for new fossil generation capacity and to provide quantitative measures of the scale and rate at which new low- or zero-carbon capacities need to be deployed, three scenarios were explored under the scenario assumptions specified in Tables 5 and 6.

In the first scenario, the Low-Carbon Scenario (referred to as the ‘LC-scenario’), no additional fossil-fueled capacity is allowed beyond 2010. Retired nuclear power and RES capacities are assumed to be replaced with similar generation technologies. The total installed capacity of nuclear power is assumed to remain at current levels throughout the studied period. Thus, the phasing out of nuclear power in Germany and Belgium is assumed to be offset by expansions of nuclear capacity elsewhere. The estimated deployment rate of RES up to 2020 is based on the National Renewable Energy Action Plans of the European Member States (ECN, 2011), corresponding to an aggregated capacity addition of approximately 235 GW.

Table 5. Nuclear and renewable capacities – scenario assumptions. The same assumptions are applied in all three scenarios.

	Installed capacity (GW) 2010	Capacity additions (GW) 2010–2020[a]	Comment(s)
Nuclear	130.9	-	The total installed capacity of nuclear power in the EU is assumed to remain at current (2010) levels throughout the studied period 2010–2050.
Biomass	22.6	21.0	The suggested deployment of renewable capacities 2010– 2020 is based on the assumption that all EU Member States fulfill their National Renewable Energy Action Plans (NREAP). The assumption is based on ECN (2011), which presents projected RES capacity additions, 2010–2020, by generation technology. Retired RES capacities are assumed to be replaced with similar generation technologies throughout the studied period of 2010–2050.
Hydro	157.4	21.8	
Of which pumped storage	39.8		
Wind			
Onshore	81.1	87.7	
Offshore	3.0	41.2	
Solar			
PV	28.8	55.6	
Thermal (CSP)	0.7	6.3	
Geothermal	0.6	1.0	
Other RES (tide, wave)	-	2.3	
Total	425.1	236.8	

[a] As stated above, the assumptions regarding investments in new capacity additions are limited to the period up to 2020. Beyond 2020, apart from nuclear and RES reinvestments, no new investments are made.

In the second scenario, the Fossil Scenario (referred to as the 'FO-scenario'), all planned and proposed fossil-fueled power plant projects listed in the Chalmers Power Plant database are assumed to be deployed in the period 2010–2020, adding approximately 150 GW of fossil-based generation capacity up to 2020. The suggested capacity additions include 40.7 GW of coal-based and 14.6 GW of lignite-based thermal power projects and 92.6 GW of natural gas-fired Combined Cycle Gas Turbines (CCGT). All other assumptions are the same as those made in the LC-scenario and as mentioned above, only presently commercially available technologies are used for reinvestments, which means that CCS is not an option that is considered in the present study.

The third scenario, the Natural Gas Scenario (referred to as the ‘NG-scenario’), is also based on the assumption that all EU Member States will fulfill their National Renewable Energy Action Plans, thereby adding 235 GW of renewable capacities up to 2020. However, in contrast to the FO-scenario, all fossil capacity additions (150 GW in total) are assumed to be natural gas CCGT plants. Thus, the assumption is made that all planned coal- and lignite-based thermal power projects are abandoned and replaced with natural gas-fired units.

Table 6. Fossil capacities – summary of assumptions for the FO-scenario and NG-scenario (see also Table 5).

	Installed capacity (GW) 2010	Share of capacity older than 20 years (%)	Share of capacity older than 40 years (%)	Capacity additions (GW) 2010–2020[a]	Comment(s)
Thermal power plants:					The suggested capacity additions in the period 2010–2020 are based on the aggregate capacity of the planned (and proposed) fossil fueled power plant projects listed in the Chalmers Power Plant database (Kjärstad and Johnsson, 2007). The cumulative capacity of the proposed projects (many associated with significant levels of uncertainty) is shown in brackets.
Coal	132.3	86	27	40.7 *(23.8)*	
Lignite	57.3	81	24	14.6 *(7.5)*	
Oil	57.3	81	14	-	
Peat	2.3	41	3	-	
Waste	3.6	15	4	0.8	
Natural gas	200.7	24	5	92.6 *(40.0)*	
Total	453.5			149.3 *(71.3)*	

[a] As stated above, assumptions regarding investments in new capacity additions are limited to the period up to 2020. Beyond 2020, apart from nuclear and RES reinvestments, no new investments are made.

2.3.2 Petroleum refining

For the oil refining sector, the CO_2 emission trajectory has been derived based on the following assumptions: (1) a decline in demand in all end-use sectors throughout the studied period and a drastic reduction in demand from the transportation sector after 2030; (2) continuous improvements in energy efficiency and an increased share of natural gas in the fuel mix; and (3) continuous changes in fuel demand and fuel specifications in the transportation sector.

The capital stock turnover approach applied to the other sectors was not applied to the oil refining industry. Instead, the process energy requirement, here referred to as the 'internal energy demand', has been directly expressed as a function of the transformation output. Within the transportation fuel segment, the market for middle distillates (i.e., diesel and aviation fuel) is assumed to continue to expand at the expense of lighter distillates (i.e., gasoline). Simultaneously, the regulations governing product quality and environmental specifications (e.g., sulfur content and aromatics) are assumed to be progressively tightened. Both trends would involve increased processing intensity and consequently, increased energy use (Szklo and Schaeffer, 2007; Tehrani and Saint-Antonin, 2008; Concawe, 2008). Thus, the effects of energy efficiency improvements are in the present study assumed to be outweighed by expansions of the conversion and treatment capacities, and to result in increases in energy intensity. While residual fuels are assumed to continue to dominate the fuel mix, the share of natural gas will increase over time (for a more comprehensive review of strategies for CO_2 abatement in the EU refining industry, see Johansson et al., 2011).

Total annual CO_2 emissions have been calculated as a function of the fuel mix and internal energy demand in EU refineries, which in turn depend on total annual output. The scenario analysis is limited to the onsite CO_2 emissions and does not include either indirect CO_2 emissions from electricity production or emissions from the combustion of petroleum fuels in the end-use sectors (which account for the majority of total emissions from the fuel chain).

Table 7 summarizes the scenario assumptions and corresponding emission factors used to generate the CO_2 emission trajectory for the EU petroleum refining industry.

Table 7. Petroleum refining – scenario summary.

	2010	2020	2050	Fuel emission factors[d] (tCO_2/GJ)
Total transformation output[a] (Mtoe/yr)	682	625	289	
Internal energy demand[b] (% of total transformation output)	7.1	7.2	7.5	
Fuel mix[c] (% of internal fuel consumption)				
- Refinery gas	55	55	59	0.057
- Residual fuel oil	17	17	10	0.078
- Other petroleum products	19	19	14	0.064–0.1
- Natural gas	9	9	17	0.055

[a] Total transformation output in 2010 from (Eurostat, 2011b). The assumption regarding the output mix in 2050 is based on European Commission's Global Climate Action Scenario (European Commission, 2011b).

[b] Estimated based on (EUROPIA, 2011)

[c] Fuel mix in 2010, estimated based (Eurostat, 2011c).

[d] Estimated based on (EEA, 2006; Reinaud, 2005).

2.3.3 Iron and steel production

For the iron and steel industry, the development in the scenario is based on: (1) capital stock turnover; (2) continued structural changes from primary (BF/BOF) to secondary (EAF) steel production; and (3) reductions in specific emissions (tCO_2/t steel) driven by efficiency improvements and fuel substitution.

As described above, the pace of capital stock turnover was assessed based on the industry's age structure and the assumed average technical lifetime of key process equipment being set to 50 years. The age structures of operating BF and EAF are given in Figure 3.

The EAF share of EU steel production is assumed to continue to increase in line with the historical trend, from 42% in 2010 to 62% in 2050. Since 1980, the secondary steelmaking share of EU crude steel production has steadily increased at the expense of primary steelmaking in integrated steel plants (Eurostat, 2002; WSA, 2011).

The combined effects of continuous improvements to existing process technologies and the replacement of decommissioned capacity with new BAT processes will contribute to lowering the average thermal energy consumption and to reducing the levels of specific emissions (tCO_2/t steel). Specific emissions from the remainder of the existing capacities are assumed to be gradually reduced from 1.55 tCO_2/t steel in 2010 to 1.49 tCO_2/t steel in 2030, and thereafter to 1.33 tCO_2/t steel in 2050. Specific emissions from new state-of-the-art plants are assumed to be 1.33 tCO_2/t steel in 2010, 1.27 tCO_2/t steel in 2030, and 1.10 tCO_2/t steel in 2050. The lower estimates for specific emissions from new primary steel capacity include the use of bio-coke as a coke substitute (Fruehan et al. 2000; Carbon Trust, 2011).

Indirect emissions from electricity production and CO_2 emissions associated with coke production and the pelletizing and sintering of iron ore have not been included in the scenario analysis.

Table 8 summarizes the scenario drivers and assumed parameter values used to generate the CO_2 emission trajectory for the EU iron and steel industry.

Table 8. Iron and steel industry – scenario summary.

	2010	2020	2050
Structure of production[a]			
Primary steel (BF/BOF) (Mt steel/yr); of which	100	108	77
- Existing capacity (%)	100	61	5
- New capacity (%)	0	39	95
Secondary steel (EAF) (Mt steel/yr); of which	72	92	123
- Existing capacity (%)	100	97	52
- New capacity (%)	0	3	48
Total crude steel production[a] (Mt steel/yr);	172	200	200
Direct specific emissions[b]			
Primary steel (tCO_2/t steel)			
- BF/BOF existing[c]	1.55	1.49	1.33
- BF/BOF new[d]	1.33	1.27	1.1
Secondary steel (tCO_2/t steel)			
- EAF existing[e]	0.10	0.10	0.10
- EAF new[f]	0.07	0.07	0.07

[a] Data on crude steel production in 2010 are taken from (WSA, 2011).

[b] Direct specific emissions do not include indirect emissions from electricity production or emissions associated with coking, pelletizing, and sintering.

[c] Starting year value based on approximate levels of specific direct emissions from EU hot metal production (Ecofys, 2009a). The end-year value is based on benchmark values for hot metal production for installations included in the EU ETS (European Commission, 2011c).

[d] Starting year value based on benchmark values for hot metal production for installations included in the EU ETS (European Commission, 2011c). The end-year value is based on estimates of minimum specific direct emissions from primary iron making (including use of bio-coke as a coke substitute) (Fruehan et al. 2000; Carbon Trust, 2011).

[e] Estimated based on average performance of existing EU EAF (Ecofys, 2009a).

[f] Estimated based on (Birat et al., 1999).

2.3.4 Cement manufacturing

For the cement industry, the methodological approach is similar to the approach used for the iron and steel industry. Thus, the scenario is based on: (1) capital stock turnover involving a continuous shift from wet to dry production processes; (2) increased utilization of alternative additives to replace cement clinker in the finished cement; and (3) a fuel shift away from coal and pet-coke towards increased use of biomass-based fuels.

Capital stock turnover is assessed based on the vintage structure of operating cement kilns (Fig. 3d) and the assumed technical lifetime of the cement kiln, here set at 50 years (OECD, 2000). Retired production capacity is assumed to be replaced with state-of-the-art dry manufacturing processes (New BAT), i.e., dry process rotary kilns with pre-heaters and pre-calciners. Similarly, retired white cement production capacity is replaced with new white cement plants (New White).

Most of the direct CO_2 emissions from the cement industry are due to the production of clinker. Approximately 60% of the CO_2 emissions are process emissions from the calcination, and the remaining CO_2 emissions are related to the combustion of fuels (IPCC, 2006; European Commission, 2010a). Consequently, by reducing the clinker content of the finished cement both the process and fuel-related CO_2 emissions can be reduced. Here, the average clinker content in the cement produced in the EU is assumed to be reduced from 75% in 2010 to 60% in 2050 (WBCSD, 2009).

Coal and pet-coke still dominate the fuel mix in EU cement kilns (European Commission, 2010a). In the analysis, the share of alternative fuels is assumed to increase from 18% in 2010 to 40% in 2050, with 40% consisting of pure biomass.

Total CO_2 emissions are calculated as the sum of process- and fuel-related CO_2 emissions. Indirect CO_2 emissions from electricity production are not included in the analysis. Table 9 summarizes the scenario assumptions and estimated parameter values used to generate the CO_2 emission trajectory for the EU cement industry.

Table 9. Cement manufacturing – scenario summary.

	2010	2020	2050	Fuel emission factors[f] (tCO_2/GJ)
Total cement production[a] (Mt cement/yr); of which	190	240	240	
- Existing capacity (%)	100	64	6	
- New capacity (%)	0	36	94	
Thermal energy consumption[b](MJ/t clinker)				
Existing capacity:				
Dry rotary kiln with pre-heater and pre-calciner (PHPC)	3590	3550	3450	
Dry rotary kiln with pre-heater without pre-calciner (PH)	3740	3700	3590	
Dry long rotary kiln (DL)	3710	3670	3560	
Semi-wet/semi-dry rotary kiln (SW/SD)	3860	3820	3710	
Wet rotary kiln (WET)	5650	5590	5430	
New capacity:				
New BAT	3100	3080	3000	
New White	5500	5430	5200	
Average thermal energy consumption (MJ/t clinker)	3770	3490	3090	
Clinker to cement ratio[c] (%)	75	71	60	
Process emissions[d] (tCO_2/t clinker)	0.51	0.51	0.51	
Fuel mix[e] (% of internal fuel consumption)				
- Pet-coke	40	38	32	0.1
- Coal	33	29	19	0.105
- Fuel oil	3	3	3	0.075
- Lignite	5	5	5	0.11
- Natural gas	1	1	1	0.055
- Alternative fuels	18	24	40	0.045–0.1[g]

[a] Cement production data for 2010 obtained from (Cembureau, 2011)

[b] Thermal energy consumption of current kiln technologies was estimated based on published studies (European Commission, 2010a; WBCSD, 2011). Data on new capacities estimated based on (Ecofys, 2009b; European Commission, 2010a).

[c] Estimated based on (WBCSD, 2009, Pardo et al., 2011).

[d] The default cement clinker is assumed to have a 65% CaO fraction (IPCC, 2006).

[e] Fuel mix in 2010 is estimated based on (European Commission, 2010a).

[f] Estimated based on (EEA, 2006;WBCSD, 2009).

[g] CO_2 emission factors for alternative fuels reduced over time as the share of biomass increases (40% biomass in alternative fuels in 2050)

3 Results

3.1 Power sector

Figure 4 summarizes the electricty generation mixes and associated CO_2 emissions for the three scenarios. Common to all the scenarios is the phase-out pattern of existing electricity generation capacities. As described above, the difference between the contribution of capacities currently in place (or under construction) and the Reference demand gives a measure of the magnitude of the increasing gap between elecritiсy demand and supply, with respect to what can be provided by currently existing capacities and those in which investment is made up to Year 2020. If one considers only the contribution from the remainder of the existing capacities, the electricity supply deficit amounts to 870 TWh in 2020, 1790 TWh in 2030, and 4060 TWh in 2050. Assuming that existing capacities are used until they reach the end of their technical lifetime, these will continue to play a major role in the electricity supply system over the coming decades, generating almost 2200 TWh in 2030, corresponding to more than half of the Reference demand. Nonetheless, by 2050, most of the existing capital stock will have been retired. Of the existing fossil-fueled capacities, only the coal-fired and lignite-fired plants (with an aggregate capacity of 16 GW) currently under construction will remain up to Year 2050. Since it is assumed that the present generation capacity will not be retired until it has reached the end of its estimated technical lifetime, possible early retirements induced by increased fuel or CO_2 costs, or other constraints, are not considered. However, with respect to the use of existing capacities, the results of this work are similar to the results obtained by Odenberger and Johnsson (2010), who have used a cost-minimizing model in which the existing capacities are either phased out when they reach the end of the technical lifetime (as in the present work) or when they become too expensive to run compared to new investments.

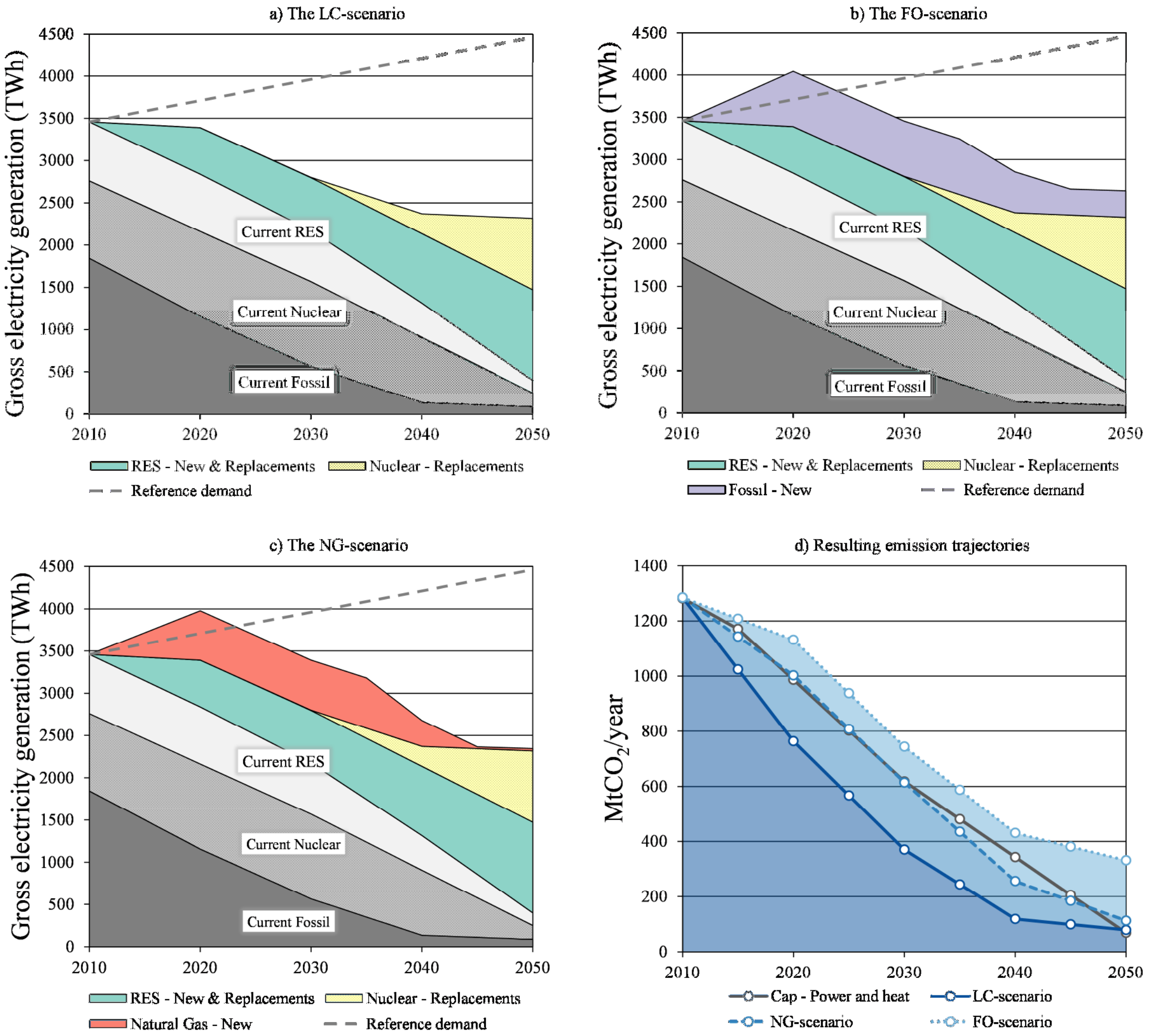

Figure 4. a–c) The power production mixes in the three scenarios for the future development of the power sector by technology and fuel type. Reference demand (dashed grey line) indicates the total gross electricity generation required to balance demand, assuming linear growth in electricity demand from 3250 TWh in 2010 to 4250 TWh in 2050. A comparison of the Reference demand and gross electricity generation in each scenario gives an indication of the magnitude of the capacity expansion required up to 2050. d) Resulting CO_2 emission trajectories from each scenario, as compared to the EU emissions reductions targets for 2020 and 2050 (cf. Table 3).

In the LC-scenario, in which new fossil fuel capacity is not allowed beyond 2010 (with the exception of plants that are currently under construction), the deployment of 240 GW of renewable capacities will compensate for most of the losses caused by the gradual retirement of the existing capital stock up to 2020. However, the RES capacity expansion projected in the National Renewable Energy Action Plans is not sufficient to meet the increased electricity demand. In 2020, total electricity generation amounts to 3390 TWh, which is 340 TWh lower than the reference electricity demand. The increasing gap between demand and supply throughout the entire period up to 2050 indicates a requirement for new generation capacity up to 2050, i.e., 1160 TWh in 2030 and 2140 TWh in 2050. Since cumulative CO_2 emissions from the remaining fossil fuel capacities in 2050 would exceed the target level (cf. Fig. 4d), this implies that the deficit would have to be met without additional CO_2 emissions. Considering also the uncertainties with respect to the future role of nuclear power, this highlights the importance of measures to overcome barriers associated with high penetration and high diffusion rates of intermittent renewables (e.g., transmission and storage issues).

In the FO-scenario, in addition to the 240 GW of RES capacity expansion assumed in the LC-scenario, 150 GW of fossil fuel power generation capacity is assumed to come online in the period 2010–2020. The suggested capacity additions would collectively generate 1200 TWh of electricity in 2020. Together with the contribution from the remainder of the current capacities, total generation would exceed the demand projected in the Reference demand up to Year 2024. To replace the decommissioned capacities and to balance demand in the medium and long terms, new investments in power capacities will be required so as to generate 500 TWh in 2030 and 1830 TWh in 2050.

The NG-scenario builds on the same assumptions as the FO-scenario, with the exception that all fossil fuel-related capacity additions in the period 2010–2020 (150 GW in total) are assumed to be natural gas CCGT plants. Consequently, the amount of electricity generated would be approximately the same as in the FO-scenario up to 2030. Thereafter, since the estimated technical lifetimes for natural gas CCGT plants are shorter than those for coal- and lignite-fired power plants, the need for new capacity investments would increase faster in the NG-scenario than in the FO-scenario.

The emission trajectories describe estimated annual CO_2 emissions from existing fossil capacities and from new fossil fuel capacity (i.e., fossil fuel capacity additions in the period 2010–2020) over the period 2010–2050. The resulting emission trajectories effectively illustrate how near-term investment decisions can have long-lasting effects on the CO_2 emissions from the power sector. With no new fossil capacity, the LC-scenario obviously offers the best chance of achieving the emission reduction targets. However, the CO_2 emissions from the remaining fossil capacities, approximately 80 $MtCO_2$/yr, would be sufficient to compromise the emission reduction target for 2050.

The emission trajectory for the FO-scenario exceeds the target trajectory throughout the studied period. The suggested fossil capacity additions would result in total annual CO_2 emissions that exceed the target levels by 15% in 2020 and 20% in 2030. In the end-year 2050, annual CO_2 emissions would amount to 330 $MtCO_2$/yr, nearly fivefold higher than the target levels. These results show how relatively modest expansions in coal-fired (41 GW) and lignite-fired (15 GW) capacities would make it increasingly difficult to meet the emission reduction targets. Thus, it is clear that any new investments in coal-fired generation must be combined with CCS.

The NG-scenario is similar to the current development with rapid growth in renewable electricity generation and a continued shift from coal to natural gas in the power sector. The analysis shows that continuation of these trends in the short term would result in emission levels in line with the target trajectory (cf. Fig. 4d). The continued expansion of the natural gas generation capacity beyond 2020 would however not be consistent with the goals outlined in the EU “Low-carbon economy roadmap” (European Commission, 2011b).

Thus, the results indicate that in addition to the assumed capacity expansion in the period 2010–2020 and the assumed RES and nuclear reinvestments in the period 2010–2050, to balance demand in the medium-terms and long-term, investments in new low- (and zero-) carbon power capacity, so as to generate 600–1000 TWh per year in 2030 and at least 2000 TWh per year in 2050 will be required to meet the emission cap, as specified in Figure 4d. Furthermore, to enable deep reductions in emissions and to avoid lock-in effects, investments in new coal-fired or lignite-fueled power plants must be avoided (unless they are combined with CCS). Similarly, the continued expansion of the natural gas generation capacity beyond 2020 has to be avoided.

3.2 Petroleum refineries

Figure 5 shows the projected annual output of petroleum products and the resulting CO_2 emissions from EU refineries. Since investments in new conversion and treatment capacities are assumed to outweigh the effects of energy efficiency improvements and since fuel switching contributes only marginally to CO_2 abatement, the most feasible way to achieve deep reductions in emissions in the refining industry is to target the end-use sectors. However, the envisaged drop in total output from EU refineries, from 682 Mtoe/yr in 2010 to 289 Mtoe/yr in 2050, would not be sufficient to meet the long-term emission reduction targets for the refinery sector. The estimated total annual CO_2 emissions would exceed the target by more than 20 $MtCO_2$/yr in 2030 and by more than 40 $MtCO_2$/yr in 2050.

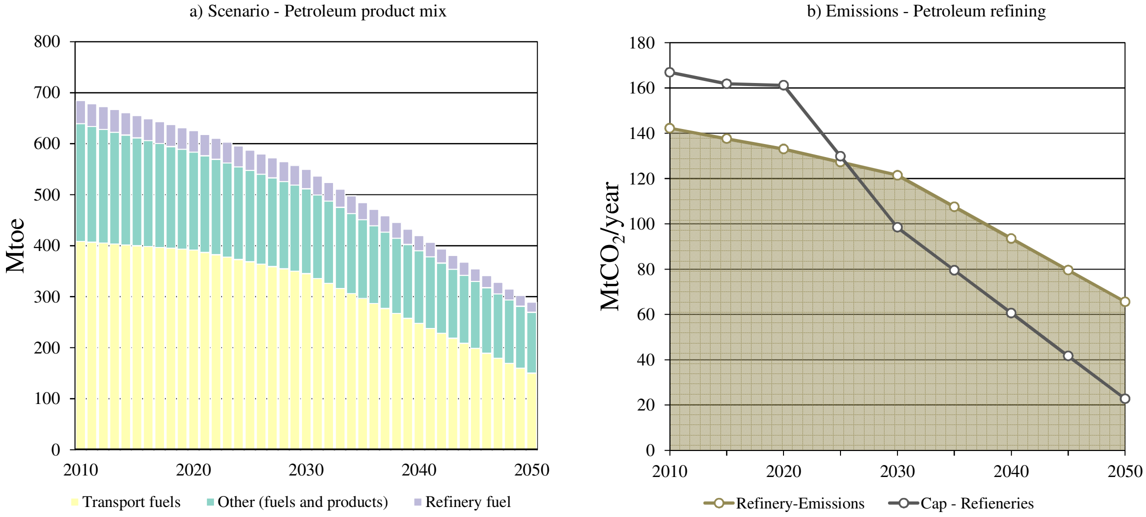

Figure 5. Total output (including own use) and CO_2 emissions from the EU petroleum refining industry in the period 2010–2050. a) The projected production mixes. Transport fuels include petroleum fuels for road, rail, aviation, and marine transportation. Other fuels and products include petroleum fuels for the power, residential, and industrial sectors and refined products for non-energy use. Refinery fuel refers to the fuels used internally in the refining process. b)The estimated CO_2 emissions from European refineries in the period 2010–2050.

3.3 Iron and steel industry

Figure 6 presents the hypothesized evolution of the EU steel sector and the projected CO_2 emissions trajectory. The simulated stock turnover suggests that a majority of the existing EU primary steel production capacity (BF/BOF-existing) will be replaced in the period up to 2030, and that only 5% of the current primary steel capacity will remain in 2050. Replacing retired capacity with BAT processes would result in a reduction of the average specific emissions from primary steel production from 1.6 tCO_2/t steel in 2010 to approximately 1.1 tCO_2/t steel in 2050. This reduction is primarily the result of the introduction of new capacities with superior thermal efficiencies. However, reducing specific emissions in line with the lower estimate would also involve the use of bio-coke as a coke substitute. Capital stock turnover, increased secondary steel production, and the introduction of bio-coke as a coke substitute would collectively result in a 40% reduction of CO_2 emissions by 2050 relative to the 2010 levels. Nevertheless, as the resulting emission trajectory shows, the cumulative effect of these measures would not be sufficient to meet the ambition of an 85% reduction in CO_2 emission by 2050.

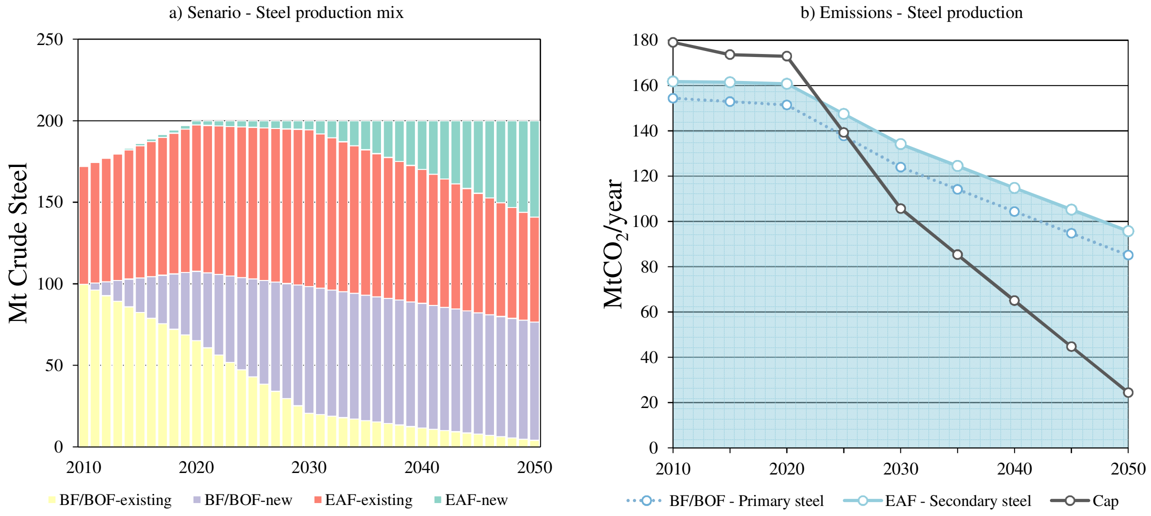

Figure 6. Evolution of crude steel production and resulting CO_2 emissions in the EU in the period 2010–2050. a) The contributions from existing and new primary (BF/BOF) and secondary (EAF) capacities, respectively. b) The estimated cumulative CO_2 emissions from EU steel production.

3.4 Cement industry

Figure 7 shows the share of EU cement production for each kiln type and the estimated annual CO_2 emissions over the period 2010–2050. The scenario for the cement industry is characterized by relatively rapid capital stock turnover. All the inefficient long dry kilns and wet production processes are phased out and replaced by state-of-the-art processes by 2030. In 2050, the plants that were commissioned after 2010 would account for 94% of the total output of cement (3% from new white cement plants), the remainder would come from plants built before 2010. This would result in a decrease in the average thermal energy consumption of the cement kiln stock, from 3770 MJ/t clinker in 2010 to 3090 MJ/t clinker. Improved thermal efficiency in combination with a reduction of the clinker content of the finished cement and an increasing share of biomass in the fuel mix would, despite the assumed output growth, lead to a reduction in combustion-related emissions, from 54 $MtCO_2$/yr in 2010 to 44 $MtCO_2$/yr in 2030 and 35 $MtCO_2$/yr in 2050. Although the process emissions are higher in 2050 than in 2010, in absolute terms, the increased use of clinker substitutes would contribute to reducing direct specific emissions from cement manufacturing. The emission trajectory describes estimated annual process- and combustion-related CO_2 emissions for the EU cement industry over the period 2010–2050. Despite the reduction in specific emissions, from 0.67 tCO_2/t cement in 2010 to 0.45 tCO_2/t cement in 2050, the assessed measures would not be sufficient to comply with the 85% emission reduction target.

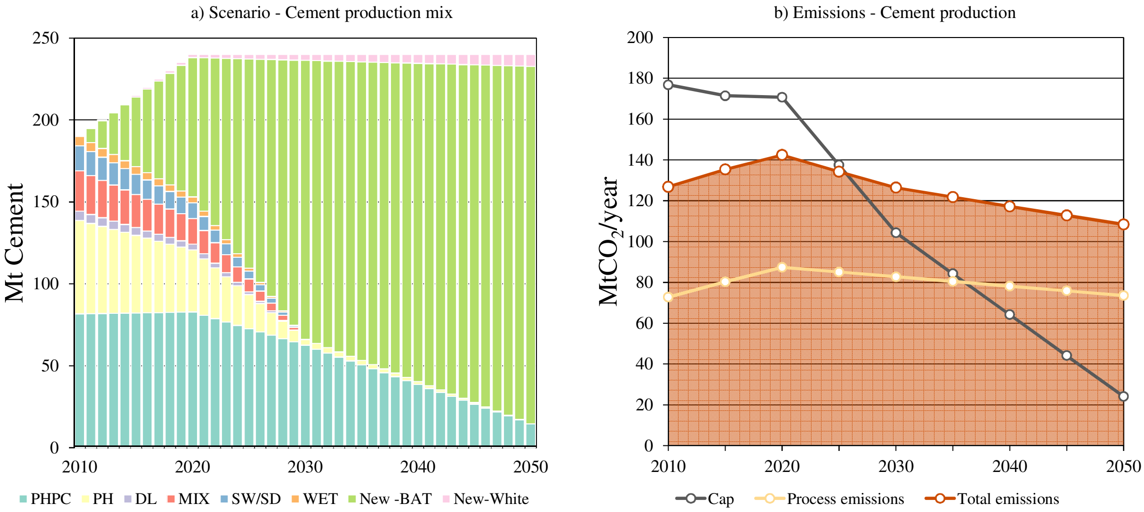

Figure 7. Evolution of cement production and corresponding CO_2 emissions from the EU cement industry, 2010–2050. a) The annual contribution to total output from each kiln type; dry rotary kiln with pre-heater and pre-calciner (PHPC); dry rotary kiln with pre-heater without pre-calciner (PH); dry long rotary kiln (DL); semi-wet/semi-dry rotary kiln (SW/SD); Wet rotary kiln (WET); new state-of-the-art kiln (New-BAT); new white kiln (New-White). b) The estimated annual CO_2 emissions from EU cement manufacturing. Total emissions include both fuel-related and process-related emissions.

3.5 Summary

To estimate the emission reduction potentials of the assessed measures, we compared the cumulative annual emissions for each of the scenarios with the emissions in the baseline case. In the baseline case, the technology and fuel mix are kept constant in all sectors throughout the studied period. Thus, while the levels of activity increase in all the sectors (with the exception of the refining sector), CO_2 emission intensities are frozen at Year 2010 levels.

Figure 8 shows the estimated reduction potentials for the power and industrial sectors for the period 2010–2050. In the short-term, overall CO_2 emissions are reduced by 13%–34%, i.e., from 1715 $MtCO_2$/yr in 2010 to 1200-1570 $MtCO_2$/yr in 2020. The results thus indicate that, provided that the RES capacity expansion projected in the

National Renewable Energy Action Plans is realized but not all the planned coal and lignite plants come online, the short-term emission reduction goal (-21% by 2020 compared to 2005) should be within reach.

The aggregated abatement potential in 2050 for the sectors investigated is estimated to be in the range of 1500–1800 $MtCO_2$. This corresponds to a 65%–80% reduction relative to the 2010 levels. As illustrated in Figure 8a, the feasibility of deep reductions in emissions is ultimately dependent upon the development of the EU electricity supply system. The upper estimate of the reduction potential, 80% below the Year 2010 levels by 2050, assumes that no additional unabated fossil fuel capacity is allowed in the power sector beyond 2010 (the LC-scenario). The lower estimate of the reduction potential, 65% below the Year 2010 levels by 2050, assumes that all fossil-fueled power plant projects currently in various stages of planning will be commissioned in the period 2010–2020 (the FO-scenario). Thus, the results indicate that if investments in new unabated coal and lignite capacities are avoided there is a reasonable chance of achieving the goal for 2050. This in turn implies that low- (and zero-) carbon power generation capacity would need to be scaled up considerably. Our estimates indicate that in addition to the assumed capacity expansion in 2010–2020 and RES and nuclear capacity replacements (see the descriptions of the LC-scenario and NG-scenario), to balance demand in the medium and long terms, investments in new power capacity will be needed to generate 600–1000 TWh/yr in 2030 and at least 2000 TWh/yr in 2050. It should be noted that these estimates are intended to provide a measure of the magnitude of the required expansion of capacity for low-carbon power generation technologies and depend strongly on the assumptions that the total installed capacity of nuclear power in the EU remain constant throughout the studied period 2010–2050 (cf. Table 5) and of linear growth in electricity demand from 3250 TWh in 2010 to 4250 TWh in 2050 (cf. Table 3).

Figure 8b summarizes the emission reduction potentials for each of the industrial sectors. Despite the extensive measures that are assumed to be implemented, the results indicate that the industrial sectors will fail to comply with the long-term reduction targets, unless a major breakthrough in new low-carbon process technologies materializes between now and 2050.

Total CO_2 emissions from industry are estimated to be 270 $MtCO_2$/yr in 2050, i.e., 40% below the Year 2010 levels and 45% below the baseline emissions. Provided that the power sector is able to comply with the target emissions trajectory, this implies that aggregate emissions from petroleum refining and iron and steel and cement manufacturing would account for more than 75% of the total emissions from the assessed sectors in 2050.

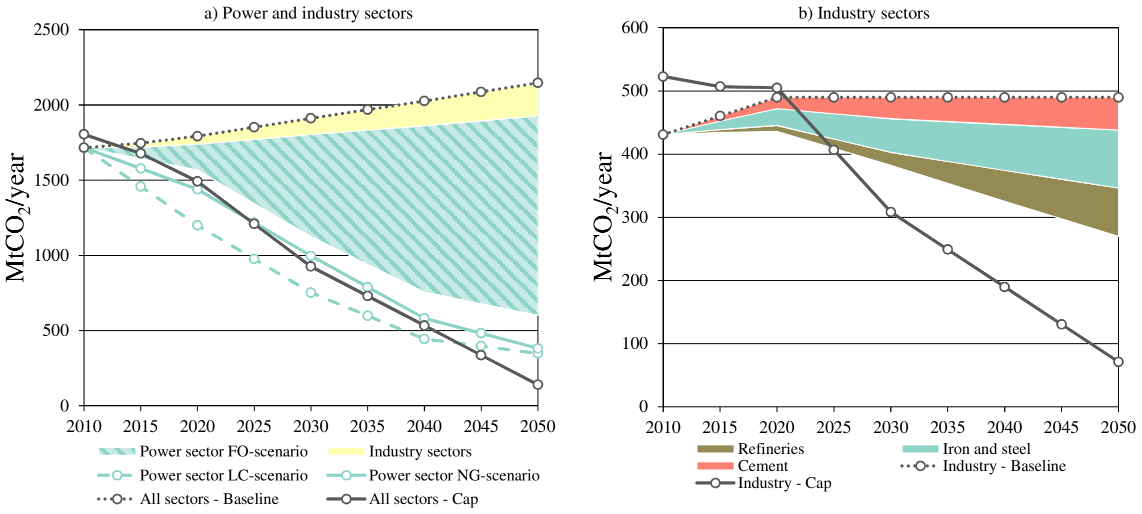

Figure 8. Emission reduction potentials relative to the baseline case in which technology and fuel mixes are frozen at 2010 levels. a) The aggregate emission reductions for the power and industrial sectors relative to the baseline case. b) The emission reductions achieved in each of the industrial sectors relative to the baseline case.

4 Discussion

Assessment of the prospects for strong reductions in CO_2 emissions from the sectors investigated in the present work obviously involves speculation about the speed of technological change. Given the time horizon of this study, significant technological change is possible and indeed likely. Thus, it may seem unwise to restrict the analysis to currently available technologies. The reason for doing so is to emphasize that many of the technologies that are expected to contribute significantly to CO_2 emission reductions are still in the early phases of development. Transformation of the power and industrial sectors to radically reduce CO_2 emissions represent a double-edged challenge. The transition involves phasing out current carbon-intensive technologies, together with the phasing in of new zero- or low-carbon technologies to fill the capacity gap. While a sufficiently high CO_2 price is a prerequisite for both these events to occur, the development and large-scale diffusion of new low- or zero-carbon technologies require additional policy measures, including RD&D funding, support for niche markets, and the adaptation of infrastructure policies (Wilson and Grubler, 2011; Azar and Sandén, 2011).

Any attempt to suggest priorities with respect to the measures that would enable significant reductions in emissions from the assessed sectors is doomed to be subjective and incomplete. Nevertheless, based on the above analysis, we have identified some key priorities, as presented in Table 10. These priorities together with the results presented in this paper may serve as the basis for further discussions. Many of the suggested measures may seem obvious but deserve to be repeated, while others are conceivably less-intuitive.

Table 10. Summary of key priorities and barriers to their implementation

	Priority	Key challenges
Power sector	Reduce demand/limit demand growth.	Demand growth in key end-use sectors driven by the shift from fossil fuels to electricity.
	Avoid any new investments in coal- and lignite-based capacities without CCS.	Several EU Member States still have untapped fossil fuel reserves.
	Develop and deploy renewable capacities	Challenges associated with high penetration of intermittent renewables still need to be resolved (i.e., transmission and storage issues). In addition, with high diffusion rates, public acceptance may be a increasing problem.
	Develop other technologies with low- or zero-carbon emissions (i.e., nuclear power and power plants equipped with CCS)	Nuclear power is supposedly the energy source that arouses the greatest controversy. Many challenges are still largely unresolved (e.g., radioactive waste disposal, nuclear proliferation, guaranteeing reactor safety). Large-scale CO_2 capture is still not commercially proven. Public acceptance may be a problem.
Petroleum refineries	Reduced demand in end-use sectors	Dependent on the development of alternative fuels/power-trains in the transport sector. May be difficult to develop credible substitutes in certain end-use sectors, e.g., fuels in aviation industry and non-fuels in petro-chemical industry.
	Fuel shift	Large-scale shifting to biomass fuels is unlikely, and the effects of a shift to natural gas are likely to be marginal.
	Develop CCS	CCS is still in its infancy (for a review, see Johansson et al., 2012).
Iron and	Improved thermal and	Minimum thermal energy requirements

steel	electric efficiencies	are theoretically and practically limited (Fruehan et al. 2000).
	Fuel shift	Coke function both as fuel and as a reducing agent, and provides the flow characteristics required in the BF in the conventional process. Thus, substitutes must provide the same ‘services’.
	Structural change	Certain market segments require high-quality primary steel. Quality standards may limit the total share of secondary steel.
	New steel-making processes (including CCS)	Alternative (low-CO_2) steel-making processes are still in the early phases of development (ULCOS, 2012).
Cement	Improved thermal and electric efficiencies	Minimum thermal energy requirements are theoretically and practically limited.
	Alternative fuel use	The maximum share of biomass that can be used in a conventional cement kiln is practically limited.
	Clinker substitution	Quality requirements may limit the use of clinker substitutes in the finished cement.
	New cement-making processes (including CCS)	Alternative (low-CO_2) cement manufacturing processes are still in the early phases of development (Croezen and Korteland, 2010)

The vintage-lifetime approach used in the present study to simulate capital stock turnover has certain drawbacks. The most important of these is the use of fixed lifetimes to represent the capital cycles of industries. As discussed by Lempert et al. (2002) and Worrell and Biermans (2005), the use of technical lifetime and age as determining factors in the retirement of industrial equipment has limitations. On the one hand, industries often have little economic incentive to retire existing plants and with regular maintenance, the capital stock may last decades longer than its nominal lifetime. On the other hand, stringent emission caps are likely to increase the rate at which old capital is retired.

In the present study, the ambition of the authors has been to make the analysis transparent and the underlying assumptions clear and explicit. However, the decisions as to what to include and what to leave out of the analysis always involve a compromise. An obvious and valid objection is that by not including economic considerations in the analysis we may have overlooked or underestimated important economic constraints and not captured the relative cost-effectiveness of the various abatement measures. Equally important, by focusing exclusively on the technological feasibility of achieving significant reductions in CO_2 emissions we do not capture the institutional and social complexities and inter-dependencies involved in the process of technological change.

5 Conclusions

This paper provides a technology-based perspective on the feasibility of deep emission reductions in the EU power and industrial sectors. The emphasis has been placed on exploring the limits for CO_2 emission abatement within existing production processes. By deliberately excluding from the analysis mitigation technologies that are still in the early phases of development (e.g., CCS), we provide an indirect measure of the requirements for new low-carbon technologies and production processes.

The results show that considerable emission reductions could be achieved with current production processes. However, to meet the emission targets of 95% reduction in the power sector and 85% reduction in the industrial sectors by 2050 (relative to year 2010), efforts to develop and deploy new low-carbon production processes will need to be accelerated. Despite assuming moderate (electricity, steel, and cement) or negative (petroleum products) output growth, an almost complete renewal of the capital stock (with the exception of the petroleum refining industry) and extensive implementation of available abatement measures, in our “best case” scenario, the total emission levels in 2050 will exceed by more than twofold the targeted levels. The results indicate that unless a major breakthrough for new low-carbon process technologies materializes in the industrial sectors, the total emissions from petroleum refineries, iron and steel plants, and cement industries in 2050 will be 270 $MtCO_2$/yr, i.e., 40% below the 2010 levels. This implies that emissions from the industrial sectors alone will account for almost a quarter of the total GHG budget in 2050 (1120 $MtCO_2$-eq/yr).

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