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Assessment of Strategies for CO_2 Abatement in the European Petroleum Refining Industry

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Abstract

Petroleum oil refineries account for almost 8% of the total CO_2 emissions from industry in the European Union (EU). In this paper, the European petroleum refining industry is investigated and the prospects for future CO_2 abatement in relation to associated infrastructure are assessed. A more efficient use of the adjacent infrastructure, e.g., district heating networks, natural gas grids, neighbouring industries, and CO_2 transport and storage systems, could provide opportunities for additional CO_2 emissions reduction. It is shown that access to infrastructures that can facilitate CO_2 abatement varies significantly across countries and between individual refineries. The assessment shows that short-term mitigation options, i.e., fuel substitution and energy efficiency measures, could reduce CO_2 emissions by 9-40 $MtCO_2$/year (6-26% of the total refinery emissions). It is further shown that carbon capture and storage offers the greatest potential for more significant emission reductions in the longer term. However, the potential for CO_2 capture varies significantly depending on the choice of technology, CO_2 source, and scope of implementation (5-80% of the total refinery emissions).

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1 Introduction

In 2008, CO_2 emissions from fossil fuel combustion in the European Union (EU) were approximately 3,780 Mt, roughly 75% of the total greenhouse gases (GHG) emissions [1]. To reduce significantly CO_2 emissions, a shift towards low-carbon production technologies is obviously needed. The petroleum refining industry is, by its very nature, part of the fossil fuel supply chain, and thus is unlikely to contribute significantly to the shift away from fossil fuels. Although CO_2 emissions from the refining process itself constitute only a relatively small share of the total emissions related to the use of petroleum fuels (approximately 8-10% [2]), total emissions from EU refineries account for 8% of the CO_2 emissions from EU industry. While both the overall CO_2 emissions and fossil fuel-related CO_2 emissions have declined in the EU since 1990, emissions from European petroleum refineries have increased by around 17%. This trend has primarily been driven by increasing demand for fuel in the transport sector. Although energy efficiency in the refining process has improved significantly over the past decades, continuing growth in the demands for diesel and significantly cleaner fuels have resulted in higher total energy consumption in refining. This so-called “petroleum refining paradox” implies that efforts to produce cleaner fuels, which would contribute to reducing emissions in the transport sector, result in increased emissions from the refineries [3].

While the share of alternative fuel is expected to grow considerably, petroleum-based fuels will most likely continue to play an important role in the transportation sector over the coming decades [4,5]. Forecasts regarding the evolution of overall demand for refined petroleum products in the transport sector and other end-use sectors vary significantly [2,6,7]. A significant reduction in the consumption of petroleum fuel will require strong policy instruments, as well as the development and diffusion of low-carbon alternatives in the end-use sectors. A key assumption in this paper is that the petroleum refinery industry will continue to play a major role in providing transport fuels in the coming decades. Therefore, assuming that EU refineries continue to supply the EU market, it is important to consider strategies to reduce the CO_2 emissions associated with the petroleum conversion process.

Since 2005, petroleum refineries within the EU have been part of the European Union Emission Trading System (EU ETS). The overall goal of the EU ETS is to reduce GHG emissions within the trading sector by 21% by 2020, relative to the 2005 levels [2]. Furthermore, in February 2011, the European Council reconfirmed the EU objective of reducing GHG emissions by 80–95% by 2050, relative to the levels in 1990 [7]. To achieve such far-reaching emission reductions, all sectors of the economy will have to contribute. In this paper, we apply scenario analysis to assess the contribution of the EU petroleum refining industry to meeting the 2050 target.

Several published studies have explored the prospects for energy efficiency and CO_2 emission reductions in the petroleum refining industry [e.g. 9-15]. These studies have focused primarily on the prospects for best practice of available technologies[1], since there are possibilities for lowering CO_2 emissions by applying already available technologies and measures. However, to realise the goal of further extensive emission cuts, new strategies for CO_2 abatement need to be introduced. Although the above-mentioned studies provide valuable information and knowledge regarding the possibilities of applying best available technologies and energy efficiency measures, there is also a need to explore alternative abatement options, such as carbon capture and storage (CCS), and to improve overall energy efficiency by means of

[1] Available technology refers to technology on the market.

district heat delivery. Several studies have investigated the potential for capturing CO_2 emissions in refineries [16-22], while other studies have estimated the district heat potential of European industries (including oil refineries) [23]. Nevertheless, there is a need to evaluate CO_2 mitigation options in relation to the potential for utilisation of the associated infrastructure (e.g., district heating networks, natural gas grid, and potential CO_2 storage sites).

The aims of the present study are to define the main characteristics of the current refining industry and to assess the technical potential for CO_2 reduction up to 2050. The analysis has been restricted to the technical potentials of available abatement options, which means that possible economical and institutional constraints have not been considered. The most important novel aspects of this paper are inclusion of the roles of associated infrastructures and the EU-level approach that is used to present the mitigation potential for the EU petroleum industry as a whole.

1.1 Description of the EU petroleum refining industry

There are currently 114 refineries in the EU27 countries, with a combined capacity of approximately 770 Mt/year. Refineries can be found in 22 out of 27 European countries, and they range in size from small simple refineries with only a few products to high-conversion cracking refineries [24]. Seven countries – Germany, the United Kingdom, Italy, France, Spain, the Netherlands, and Belgium – account for 75% of the total crude oil capacity of the refineries in the EU, as well as 75% of the total CO_2 emissions from the oil refining industry in the EU.

More than 90% of the European refineries were built before 1980 [12]. While most European refineries were originally built to produce petrol for cars and fuel oil for power generation, the product demand has gradually become more diversified [25]. The refineries that are currently in operation differ with respect to configuration, process integration, feedstock, feedstock flexibility, products, product mixture, design, and control systems. These variations depend on many factors, such as owner strategy, market situation, location, age of refinery, historical development, available infrastructure, and local regulations. Nevertheless, these refineries can be assigned to a limited number of types, and there are a number of methods to characterise the complexity of a refinery. In the present study, the categorisation of configurations is based on the categories defined by the IPPC [12] and Reinaud [26], which are briefly described in Table 1.

Table1. Refinery configurations [10, 12].

Simple and Base oil refinery	The production includes no conversion units, which makes these refineries limited to the production of heavy fuel oil.
Configuration 1	The simplest type of oil refinery. These refineries are equipped with a distillation unit, naphtha reformer, and some necessary treatment facility.
Configuration 2	Can convert fuel oil to a more valuable fuel by adding a vacuum distillate unit and a catalytic cracker to the hydro process above.
Configuration 3	Has a hydro cracker, which maximises the production of gasoline and middle distillates and allows the production of high-quality diesel.
Configuration 4	Has both hydro cracking and catalytic cracking units. Some refineries have an IGCC unit, which converts solids and heavy fuels to power, co-generation steam, and lighter products. Eleven refineries in the EU-27 countries have a coker unit, which reduces heavy fuel oil and produces a low-value product, coke.

Most of the 114 refineries in the EU belong to the first two configuration categories (Table 1). Only 18 refineries operate with high complexity and a large number of converting units (processes that upgrade heavy oil products to more valuable products, e.g., diesel, aviation fuel, and petroleum coke).

Table 2 presents an overview of the refinery sector in Europe and shows the number of refineries, crude oil capacity, and CO_2 emissions, as well as the complexity of all the EU refineries.

Table 2. Key characteristics of the petroleum refinery stock in Europe [27].

	Number of refineries	**Crude oil [Mb/d]**	**CO_2 emissions[Mt/year]**	**Divided by complexity**				
				Base+Conf. 1	Conf. 2	Conf. 3	Conf. 4	Unknown
EU plus Norway	114	16	155	34	45	14	18	3

Figure 1 shows the production of petroleum products in the EU refineries, divided by country, and the relative use of internal fuel. A significant share, typically around 80%, of the fuel used in the refining process is generated internally as by-products during the processing of the crude oil. Additional fuels include natural gas, electricity, and heat.

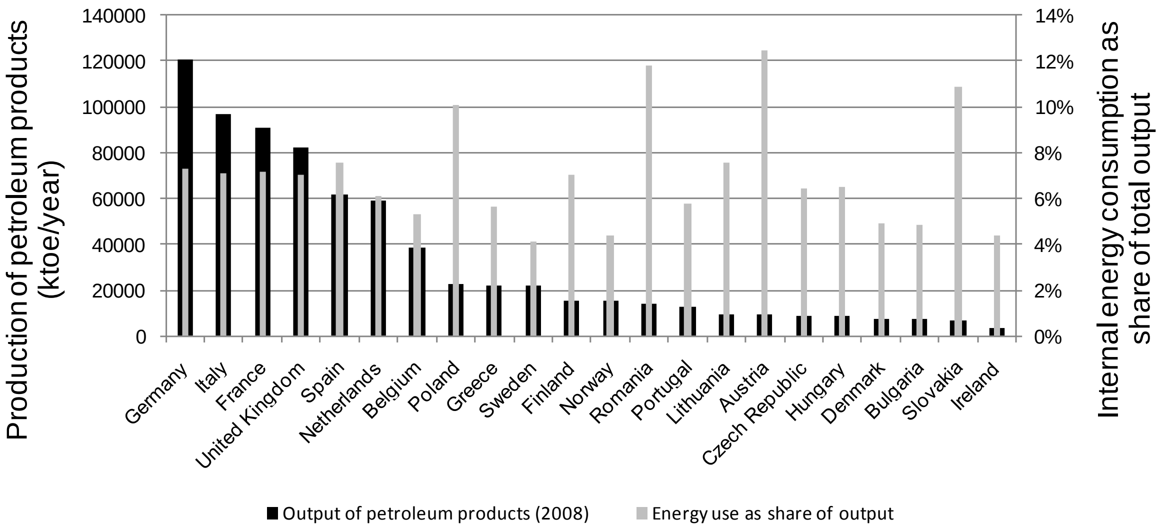

Fig.1. Output of petroleum products in ktoe/year (black bars) and internal energy consumption as share of total output given in percent (grey bars). Data source: [32].

2 Methodology

The present study covers petroleum refining in the EU and Norway. By analysing factors relevant to future CO_2 emissions, e.g., current status, activity level, market trends, and available abatement options, we assess the long-term prospects for CO_2 emission reductions in the EU petroleum refining industry. The general methodological approach involves:

- Assessment of key characteristics (e.g., CO_2 emissions, crude oil capacity, complexity etc.)
- Assessment of future trends (e.g., in fuel demand and fuel quality requirements)
- Identification of suitable mitigation options
- Assessments of adjacent infrastructures (i.e., district heating networks, natural gas grids, and potential CCS clusters)
- Analysis of the aggregate potential for CO_2 emission reductions

2.1 Analytical approach

2.1.1 Key characteristics

The starting point of the analysis has been a description of the current status of the EU petroleum refining industry. As part of the study, the Chalmers Industry database (see [16, 28] for a more detailed description of the Chalmers Energy Infrastructure databases) has been updated with facility-level data for the European refinery industry, including:

- The exact locations of the plants, i.e., country, city, address, and geographical coordinates;

- Emissions and allocated emission allowances, with inclusion of installation-level data on verified CO_2 emissions, allocated emission allowances for the period 2005–2010, and allocated emission allowances for 2005–2012;
- Refinery configurations and capacities; refineries are classified based on configuration and the database includes information on crude input, main process equipment (defined in [27]), and the process capacities for this equipment.

The current technology and fuel mix and associated CO_2 emissions have been used as references when assessing future abatement strategies.

2.1.2 Key market trends

Changes in fuel demand and fuel specifications will affect the future CO_2 balance in refineries. Therefore, scenarios that describe future fuel market trends and trends for fuel quality requirements have been examined by reviewing studies from EU institutions [24,29] and industry associations [30,31], and by collecting data from official statistical databases [32] and reports [26,31].

Two key trends that have had, and most likely will continue to have implications for EU refinery energy use and CO_2 emissions have been identified and considered in the analysis:

- The demand for heavy fuel oil has been decreasing 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). A continuous increase in the diesel/gasoline ratio will require investments in new process capacity to maximise the yield of middle distillates. Investments in such new processing units (e.g., hydro cracking) will likely lead to increased refinery energy consumption and CO_2 emissions.

- Legislation governing product quality and environmental specifications (e.g., sulfur content and aromatics) has gradually been tightened. To meet the more stringent specifications for sulfur content that have been proposed, significant investments in additional desulfurisation capacity will be required. This would involve increased processing intensity and consequently, increased energy use and associated CO_2 emissions (see e.g. [33]).

Therefore, although the present analysis is based on the assumption that overall demand will remain relatively constant, we have tried to illustrate and discuss the effects of changes in the product mix.

2.1.3 Review of mitigation options

Emphasis has been placed on mitigation options that can be translated to the EU petroleum refining industry using the information about the refining industry in the Chalmers Industry database (see Section 2.1.1). The abatement options that have been selected for further evaluation are those that are expected to generate substantial CO_2 emission reductions (both at the refinery and in terms of global CO_2 emissions). Abatement options are divided into strategies for on-site CO_2 emission reductions and off-site CO_2 emission reductions. The abatement options for on-site CO_2 emission reductions assessed here include:

- Energy efficiency measures
- Fuel shift (natural gas or biomass)
- CO_2 capture.

Abatement strategies contributing to off-site CO_2 emission cuts (i.e., global CO_2 emission reductions) include:

- Utilisation of excess heat for district heating or biomass drying
- Process integration between adjacent industries.

Mitigation options that have been recognised but that are not included in the present study include:

- Crude oil change, whereby the use of lighter crude oil would reduce energy requirements in the refining process and consequently, reduce CO_2 emissions. However, since the database does not include information on the origin of the crude oil processed in EU refineries, the effects of increased use of lighter crude have not been evaluated.
- Improved in-house power generation. Most refineries have some form of on-site power generation. Increased in-house generation (e.g., by application of CHP, gas turbines, steam turbines, high-temperature CHP and IGCC, and gasification of heavy bottom residues and refinery residues) could be a way to optimise energy use and reduce global CO_2 emissions. Szklo and Schaeffer [9] have presented an overview of integrated alternative energy systems, including the possibility of gasifying heavy solids at the refinery. Branco et al. [34] have discussed the advantages of increased complexity and versatility in future refineries, including the gasification of petroleum coke. However, as detailed energy balances for individual refineries are generally not disclosed, the potential for CO_2 emission reduction due to increased in-house electricity generation is not considered in this paper. Nonetheless, using publicly available information and cogeneration potential estimates Marín-Sánchez and Rodríguez-Toral [35] have estimated the potential for cogeneration of refinery residuals in Mexico. They have shown that installing IGCC using only vacuum residues could in a best-case scenario reduce natural gas imports by 19.6%. They have

also shown that this would increase CO_2 emissions. No CO_2 capture is considered in that study, although the authors state that such a system would be desirable at a later stage of the cogeneration projects.

- The production of renewable products is not included in the present assessment, since the study is limited to process-related CO_2 emissions.

2.1.4 Analysis of availability of associated energy infrastructure

The potential for CO_2 reduction depends to a great extent on developments in other sectors. For example, the possibility to capture CO_2 depends on a future infrastructure for CO_2 transportation, and the utilisation of excess heat for district heating depends on available district heating networks and demand for heat. To take this into account when assessing the mitigation potential, distances to currently available and possible future relevant infrastructures (i.e., CCS storage sites) have been analysed. To make the analysis of such adjacent energy infrastructure feasible, emphasis in this part of the analysis has been placed on refineries with CO_2 emissions exceeding 1 $MtCO_2$/year (total of 58 refineries), accounting for more than 80% of the total CO_2 emissions from the refinery sector. Distances and connections to district heating networks, natural gas grids, adjacent industries, and possible CO_2 storage sites have been evaluated for each of these 58 refineries separately (the data are taken from the databases described above), in order to gain a more realistic estimate of CO_2 mitigation potential.

To investigate potential synergy effects that could facilitate CO_2 mitigation, the refineries (with CO_2 emissions exceeding1 $MtCO_2$/year) in the industrial database have been updated with the distance to the following infrastructures (when available):

- District heating network
- Natural gas grid

- Nearby industries (i.e., chemical manufacturers)
- Possible CO_2 storage sites and capture clusters

In this study, it is assumed that the excess heat from the process can be used for district heat or the drying of biomass. In the case of district heat delivery, we have investigated where refineries are located close to existing networks. District heating networks are represented by geographical coordinates and distance from the refinery. Information on current district heating systems has been compiled from district heating associations, energy companies, district heating reports, heat and power companies, personal contacts, and national statistics, as well as the previous work of Engelmeier et al.[36]. Only the locations of current district heating networks are taken into account. Thus, the possible heat demand of available district heating networks is not included in the study. The maximum possible distance to deliver district heat is assumed to be 50 km. This is based on the fact that today the longest distance of heat delivery is 40 km, in Prague [36], although several projects at the planning stage are considering longer distances.

The natural gas grids are represented by geographical coordinates, and distribution data are collected from previous studies [36–42]. It is assumed, based on the continuing trend of expansion of natural gas networks [43], that all refineries currently located <40 km from a natural gas grid will have the potential to connect to natural gas grids in a future perspective.

Geographical coordinates for nearby industries are represented by chemical industries with NACE codes 185–193, chemical and base chemical industries, as well as primary plastic producers [44].

The analysis of possible CO_2 storage sites is based on data from the Chalmers database and adjusted to the information obtained from other authors [28, 45, 46]. Capture clusters are herein defined as regions with high densities of large stationary CO_2 emission sources (i.e., power plants and heavy industries with CO_2 emissions exceeding 0.5 $MtCO_2$/year). Coordinating CO_2 transport between large point sources within a limited geographical area could be one strategy for reducing transport costs. However, it should be noted that technologies for large-scale CCS are still in the early stages of development. The question as to how to implement an infrastructure for capture, transport, and storage of CO_2 remains to be resolved.

2.1.5 Analysis of the aggregate potential for CO_2 emission reductions

Finally, by combining inputs from the assessment of the current status of the refinery industry and the review of potentials for various abatement strategies with the results from the analysis of adjacent infrastructures, an assessment of the CO_2 mitigation potential is made. Here, the results from the detailed analysis of adjacent energy systems for the 58 refineries are scaled to include all refineries in Europe (114 in total). However, one exception is the energy efficiency potential, which is assessed using the results from [30] and three levels of energy efficiency based on previous research.

To assess the magnitudes of the different CO_2 mitigation options, the results are compared with the future CO_2 emissions trend for the petroleum refining industry, whereby CO_2 emissions are assumed to increase due to a continuing increase in demand for lighter fuels.

The estimates are intended to serve as illustrations of the relative potential for key abatement options, i.e., as first estimates. The potential for the respective abatement option is analysed and presented individually. It should be noted that implementation of one measure often influences the potentials of other measures and therefore, it is not possible to add up the individual potentials for the respective abatement options to obtain an overall reduction potential.

2.2 Key assumptions

2.2.1 Energy efficiency opportunities

Several opportunities exist within the petroleum refinery industry to reduce energy consumption while maintaining or even enhancing the productivity of the plant. Between 1990 and 2005, the EU refineries have increased the efficiency of their operations by an estimated 13% [30].The combined effects of improved energy management, upgrading of existing plant components, and gradual replacement of existing process technologies with new process equipment are here assumed to result in an aggregate potential for improved efficiency in the range of 5–20% over the studied period. Our assumptions are based on a review of a selection of efficiency measures reported in the literature, described below. It should be noted that enhanced energy efficiency and reduced CO_2 emissions do not necessarily correlate, and that the prospects for further improvements in energy efficiency vary significantly across individual refineries. However, our assumptions regarding the overall potential for energy efficiency improvements are in line with the estimates in the literature.

Several energy audits have been conducted that show significant potential for energy savings in the petroleum refining industry. For example, an energy assessment study conducted in 2001 at a refinery in California identified energy savings of 12% of the total energy used at the plant [47]. Most heat integration studies have been conducted on part of the refinery process, e.g. [47-51]. Total site analysis has been applied by refineries all over the world to identify the optimal utility levels. The energy saving potential for all subsystems is not always equal to the energy saving potential for the whole system, as illustrated e.g. in [52]. Worrell and Galitsky [10], based on a survey of US refinery operations, calculated typical energy savings of 20–30%, with these savings limited to 10–15% when the economic potential was considered. Worrell and Galitsky provided a list of over 100 potential energy savings measures, including: use of co-generation; improved heat integration; combustion optimisation; control of compressed air and steam leaks; and use of efficient electrical devices. According to Petrick and Pellegrino [53], in the medium-to-long-term perspective, an energy saving potential of 15–20% for the US refining industry is feasible. Szklo and Schaeffer [9] have estimated the impact on energy savings of technology alternatives for saving energy or removing sulfur in oil refineries, and suggest a near-to-medium-term net energy saving potential that ranges from 10% to 20%. Table 3 summarises the energy saving potentials for a selection of measures described in the literature.

Table 3. Energy saving potentials for a selection of measures described in the literature.

	Szklo & Schaeffer [9]	**Alsema [54]**	**Petrick & Pellegrino [53]**	**Worrell and Galitsky [10]**
Heat integration and waste heat recovery	10%[a]	6%[b]	5% (20–40%)[c]	10–30%[d]
Fouling mitigation	2%	2%	2%	0.7–3.4%[e]
Advanced process control	2%	2.5%		2–18%
Combustion efficiency improvements			7%	13–33%[f]
Advanced turbine systems/Co-generation			2 %	
Thermal cracking	17%	18%	5%	
Membrane technology[g]	-	-	-	-
Pumps	1%[h]			2–17%[j]
Biodesulphurisation	70–80%[i]	4.4%	2%	
Oxidative desulfurisation process (ODP)	40%[k]			
Catalytic distillation (CD) process	62%[l]			
Advanced catalyst for Fluid Catalytic Cracker (FCC) and		15%		

hydroprocessing

[a] Includes: use of waste heat in absorption refrigeration systems; use of waste heat to pre-heat feeds; heat and/or mass (water and hydrogen) integration using Pinch techniques; improvement of furnace efficiencies in combination with computer-controlled combustion; direct feeding of “intermediary products” to process without cooling or storage; use of heat pumps; decreased film temperature and increased turbulence on heat transfer surfaces; insulation of buildings and process units; and adoption of steam management.
[b] Includes: improved heat management and waste heat recovery; and process integration and cross-industry optimisation.
[c] This number is based on energy savings reported from several pinch analyses [53].
[d] Based on several pinch analyses conducted at different refineries.
[e] The second number is from [55], translated into percentage of the specific energy consumption of Brazilian refineries [9]
[f] Includes: improved process control; reduced flue gas quality; improved insulation; boiler maintenance, and flue gas heat recovery.
[g] The actual savings achieved with membrane separation are unclear. None of the studies found this option to be very promising. Petrick and Pellegrino [53] do not even mention this option.
[h] Percentage of electricity consumption.
[i] Reported by Linguist and Pacheco [53], in [9]. Percentage relative to conventional hydrodesulfurisation.
[j] Percentage of energy consumption by pumps.
[k] Percentage relative to conventional hydrodesulfurisation.
[l] Percentage relative to conventional hydrodesulfurisation.

According to Szklo and Schaeffer [9], waste heat recovery is one of the most important options in the short-to-medium-term perspective, while fouling mitigation and new refining processes are promising technologies in the medium-to-long-term perspective.

The four studies referred to in Table 3 were conducted in the Brazilian, Dutch, and US refinery industries. When assessing the results from different studies it is important to keep in mind the differences in these refinery industries. For example, while steam cracking is commonly used in Europe[1], fluid catalytic cracking is the most important cracking process in the US[2] and Brazil[3]. Furthermore, the US refinery industry is less energy-efficient than the Dutch refinery industry [54]. Refineries in EU countries, with the exceptions of Poland, Finland, Romania, Austria, and Slovakia, have, as shown in Figure 1, internal energy consumption as a share of total output equal to or less than that of an average Dutch refinery

[1] FCC accounts for 14–21% of the crude oil capacity in Europe [12, 27]. Thermal cracking operations account for 10% of the crude oil capacity in Europe [27]
[2]FCC accounts for 32–35% of the crude oil capacity of the US refinery industry [10, 27]. Thermal cracking operations account for 0.2% of the crude oil capacity in Europe [27]
[3]FCC accounts for 26 % of the crude oil capacity of the Brazilian refinery industry [27]. Thermal cracking operations account for 0.5% of the crude oil capacity of Brazilian oil refineries.

(6%). Alsema [54] has argued that waste heat recovery has already been addressed at Dutch refineries and that some of the options discussed by Petrick and Pellegrino [53] might not be applicable to Dutch refineries. Given the more energy-efficient refinery industry in Europe, it is reasonable to assume that it has a lower energy saving potential for heat integration and waste heat integration than the US petroleum industry.

For efficient transport and use of raw material, chemical industries are often located close to each other and to refineries. Such cluster formations create opportunities for site-wide process integration studies [57 – 59], which often show large potential for energy savings; 20–25%; on average compared to the current energy usage of the cluster [60]. A total site analysis conducted at a chemical cluster in Sweden showed a potential energy saving of 60 MW, which was expected to be achieved by moderate changes to the process utility system, corresponding to 50% of the site's total steam demand [61].

2.2.2 Fuel substitution

The majority of fuels burned in a refinery are generated by the process as light hydrocarbons (C1-C2), i.e., refinery gases. However, these top fractions are not sufficient to cover the whole energy demand. The remaining energy need (about 23% on average) has traditionally been met by low-value liquid residues. Replacing the liquid fuel with natural gas could be a way to lower the CO_2 emissions, as the emission factor from the liquid refinery fuel is approximately 0.075 kgCO_2/GJ, as compared to 0.055 kgCO_2/GJ for methane [30]. The estimation of the potential for fuel substitution is based on the assumption that refineries with access to natural gas grids replace all liquid fuels with natural gas.

2.2.3 Carbon Capture and Storage

CCS is generally assumed to offer the greatest promise for large reductions in CO_2 emissions in the refining industry. In the present study, several strategies for the implementation of CCS have been assessed. The estimates refer to the long-term potential (up to 2050) for the EU petroleum refining industry as a whole, without consideration of possible economical or institutional constraints. Table 4 summarises the estimated CO_2 recovery rates for the capture options considered in the analysis.

Table 4. Breakdown of CO_2 emissions from a petroleum refinery

	Fraction of CO_2 emissions
All sources[a]:	
Furnaces and boilers	65%
Regeneration of catalytic cracker catalyst	16%
Power (55% imported)	13%
Other sources	6%
Major isolated sources[b]:	
FCC	20%–45%
Hydrogen manufacture	5%–20%

[a] Based on [67]. Other emission sources include flaring, methane steam reforming, effluent processing, and incineration.
[b] Based on [17, 22, 63]

There are four general concepts for CO_2 capture, all of which could in principle be applied to the petroleum refining process:

- Pre-combustion processes, in which carbon is separated from the fuel before combustion.
- Post-combustion processes, in which CO_2 is removed from the flue gases.
- Oxyfuel combustion, in which fuel is combusted in oxygen (mixed with recirculated flue gas) instead of air, creating a more or less pure CO_2 stream in the off gases.
- Chemical-looping combustion, which is a combustion technology that involves inherent CO_2 separation without energy penalty from the separation of gases (i.e., the separation of oxygen from air or separation of CO_2 from the flue gases is avoided).

To date, most work on CCS in the refining industry has been focused on two of these processes; post-combustion capture and oxyfuel combustion [15, 17, 18, 62 – 66].

The total CO_2 emissions from a refinery are the sum of several emission sources of varying size. The flue gases from these different sources have different properties and have varying degrees of suitability for CO_2 capture. As indicated in Table 4, process heaters and steam boilers account for the major share of the CO_2 emitted from a typical refinery.

While it would be technically feasible to combine a number of sources and route all the flue gases to one CO_2 capture plant, this would require several kilometres of ducting (i.e., for transport) and additional blower duty (i.e., to overcome pressure drops) [21]. Thus, such strategy would therefore entail significant costs and require space for the infrastructure [17, 66]. Therefore, most studies focus on capturing CO_2 from the largest sources or the sources with the highest CO_2 concentrations. As shown in Table 5, the estimated capture costs and recovery rates vary significantly depending on the targeted CO_2 sources and the choice of capture technology.

Table 5. Characteristics of the capture options considered in the assessment.

Targeted flue gas streams	CO_2 concentration in gas stream[d] (% by gas volume)	Capture technology	Cost per tonne of CO_2 captured (€/t)	Average recovery rate (% of plants total CO_2 emission)
Furnaces and boilers[a]	3–13	Oxyfuel combustion	~30	65
CHP plant + FCC[b]		Post-combustion	~45	80
		Post-combustion	-[d]	40
FCC[c]	10–20	Oxyfuel combustion	-[d]	40
Hydrogen manufacture[e]	20–99	Post-combustion	~24 - 53	12.5
CHP plant + FCC + gas turbine + two Combined stacks[f]	4–13	Post-combustion	~90–120	40

[a] Estimations based on [68,69].
[b] Estimations based on [70].
[c] Estimations based on [63].
[d] No monetary cost estimates presented. The capture cost is estimated to be 45% lower in the oxyfiring case than in the post-combustion case.
[e] Estimations based on [15,71].
[f] Estimations based on [17]

Another important aspect is to what extent refineries with capture can be integrated in a network infrastructure for transport and storage of the captured CO_2. There are several examples of studies that have attempted to match CO_2 emission sources with suitable storage sites, but only a few concern industry emission sources [16, 72, 73]. Rootzén et al. [16] have shown that the best matches of sources to sinks in Europe are currently found in regions bordering the North Sea (assuming that off-shore storage will be favoured).

2.2.4 Utilisation of excess heat

The refining process generates large amounts of excess heat at different temperature levels. This excess heat can be utilised for district heating, low electricity generation or biomass drying. The excess heat levels from European refineries are not readily available. Therefore, in the present study, we have estimated the amounts of excess heat produced by European refineries based on the information on excess heat from two refineries (Configurations 4 and 1) given in a study by Johansson et al. [19]. In that study, the amount of excess heat above 90°C is 230 MW for the refinery with Configuration 4 and 110 MW for the refinery with Configuration 1. If the amount of excess heat is divided by the crude oil capacity of the refineries, similar levels of excess heat emerge (19.8 W/ton crude oil and 17.8 W/ton crude oil, respectively). Consequently, the main assumption regarding utilisation of excess heat is for excess heat of 18.8 W/ton crude oil for all refineries in Europe (which must be seen as the maximum amount of excess heat). In order to calculate the excess heat from all refineries, a load factor of approximately 90% is assumed [74].

Some refineries in the EU already utilise excess heat for district heating, e.g., in Sweden (1,127 GWh in 2007), Denmark (0.4 GWh from the Shell refinery in Fredericia), Austria (8–64 GWh from Raffinerie Schwechat), Italy, and the Netherlands. There is still capacity for the utilisation of more excess heat. One example is Esso’s refinery in Slangentangen, Norway, which has the possibility to deliver 800 GWh of excess heat, but lacks a market for the heat. Esso is actively working on finding solutions for the utilisation of this otherwise wasted heat [75]. Another example is the Preem Refinery in Lysekil, Sweden, which also has a large capacity for utilisation of excess heat but has a limited district heating market.

By providing excess heat for district heating, integrating process flows with nearby industries, and replacing the fossil fuel feedstock with renewable feedstock (e.g., to produce renewable diesel), refineries could contribute to reducing CO_2 emissions off-plant. District heat delivery from the refinery has the potential to reduce CO_2 emissions from the building sector, and replacing fossil fuels with renewable products will contribute to a reduction of CO_2 emissions in the transport sector. The magnitude of reduction will depend on the CO_2 effect of the marginal technology for heat generation and the transport fuel replaced.

The potential for utilisation of excess heat depends on several factors, e.g., heat demand in the network, availability of a district heating network, and support from authorities and other suppliers and consumers. The profitability of delivering district heat depends on the distance to the customer and the delivery capacity of the system.

3 Results

3.1 Assessment of associated infrastructure

To make an analysis of current associated energy infrastructures feasible, the more detailed analysis is limited to the 58 most CO_2 emission-intensive refineries (with CO_2 emissions exceeding 1 Mt/year). These 58 refineries are represented in all EU member states (plus Norway) with petroleum refining capacity, with the exceptions of the Czech Republic, Denmark, and Ireland.

Figure 2 shows the 58 refineries with highest CO_2 emissions and current adjacent infrastructure. Possible areas suitable for carbon storage are also shown in the figure. It is clear that most refineries are located close to at least one energy infrastructural system that could facilitate CO_2 mitigation. For example, almost all the refineries are located close to a natural gas grid. As illustrated in Figure 2, the potential, based on the current infrastructure, to utilise adjacent infrastructures varies significantly across countries. Refineries located along the North Sea coastline and in the west of Germany generally have the most advantageous locations with respect to adjacent infrastructures.

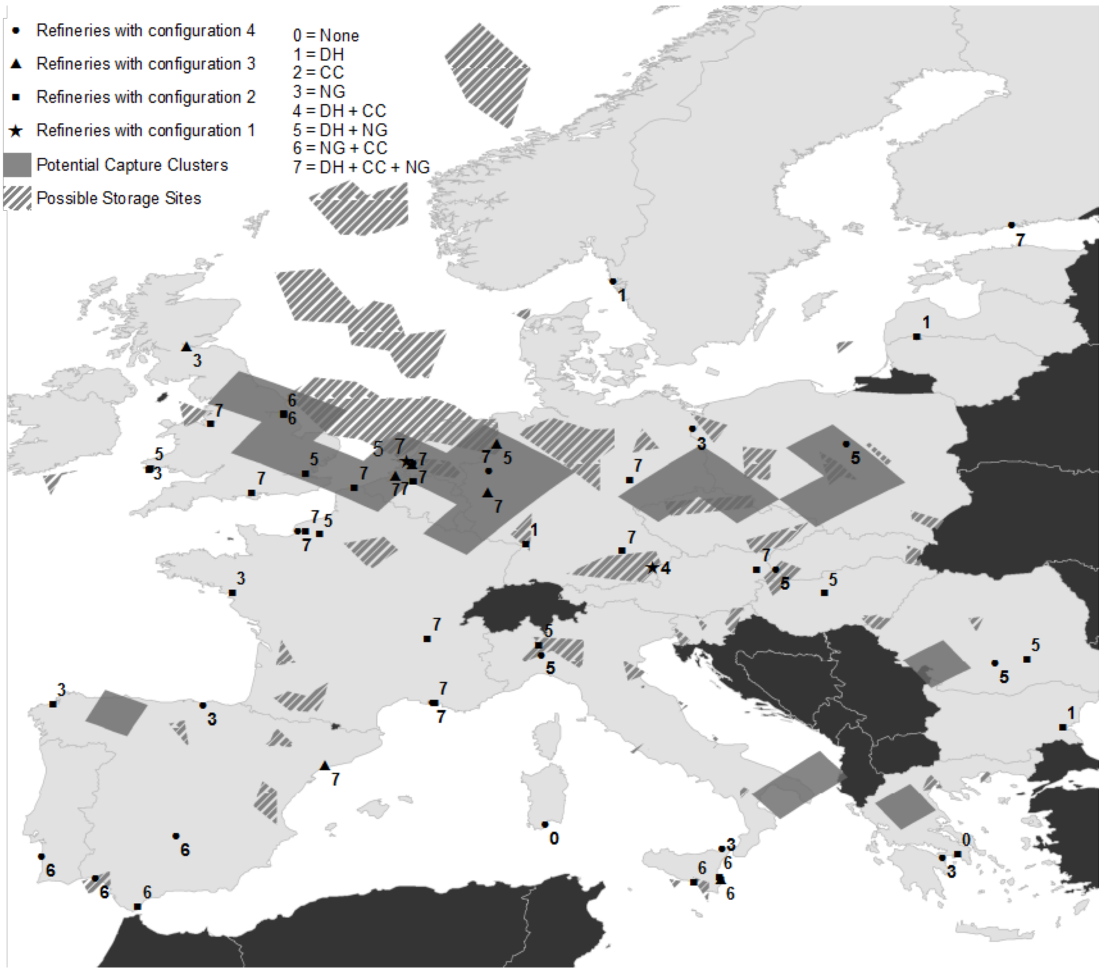

Fig. 2. Geographical distribution of refineries with CO_2 emissions >1 Mt/year in relation to district heating systems (DH), chemical clusters (CC), and natural gas grids (NG). The numbering indicates the combination of different adjacent infrastructures. Possible CO_2 storage sites are represented by grey lines. Potential capture clusters, regions where emissions from large stationary point sources (including also power plants, iron and steel industries, cement plants and pulp and paper plants) exceed 20 $MtCO_2$ annually, are highlighted in grey. This map includes the intellectual property of the European National Mapping and Cadastral agencies and is licensed on behalf of these agencies by EuroGeographics.

Regarding the prospects for implementing the CCS technology, refineries would likely benefit if they could coordinate CO_2 transport with other industries, the power industry in particular.

Areas highlighted in grey on the map represent regions with favourable conditions for the clustering of emission sources (i.e., regions with several large stationary CO_2 emission sources). The map shows that only 14 of the 58 refineries are located in such regions.

As to the prospects for implementing energy efficiency measures, refineries could benefit from coordinating energy efficiency measures and process flows with other industries, especially chemical industries located in clusters. Industrial process cluster sites can also be attractive for emerging biorefinery concepts with a focus on large-scale conversion of biomass to high-grade materials and fuel energy products. The largest chemical clusters that include refineries are located in the Netherlands, Belgium, France, Germany, and the UK. However, most of the refineries in Europe are located close to (<10 km) at least two chemical industries.

The total amount of excess heat from European refineries is in this paper estimated to be maximally 113 TWh (roughly corresponding to 3% of the heat demand of the EU residential sector). However, the potential for district heating is limited by access to district heating networks. Refineries with possibilities for nearby access to available district heating systems are obviously associated with countries that have high district heating market saturation, such as Sweden, Finland, and Lithuania, as well as countries with high annual district heating growth rates, such as Norway and Austria. In addition, in Bulgaria, Belgium, France, Germany, Romania, Slovakia, Hungary, and the Netherlands, district heating systems are found within 50 km of the refineries.

More complex refineries have greater possibilities to diversify and change their production mix, and thus can be expected to be more flexible with regards to changes in the fuel demand from the transport sector and thus more likely to survive. Complex refineries are spread throughout Europe. However, most of these refineries are located along the Mediterranean Sea and the North Sea. Three out of eighteen complex refineries (denoted with black dots in Fig. 2) are located in areas with favourable conditions for the clustering of CO_2 emissions.

3.2 Estimates of CO_2 emission reduction potentials

Figure 3 summarises the derived CO_2 abatement potentials for the assessed options.

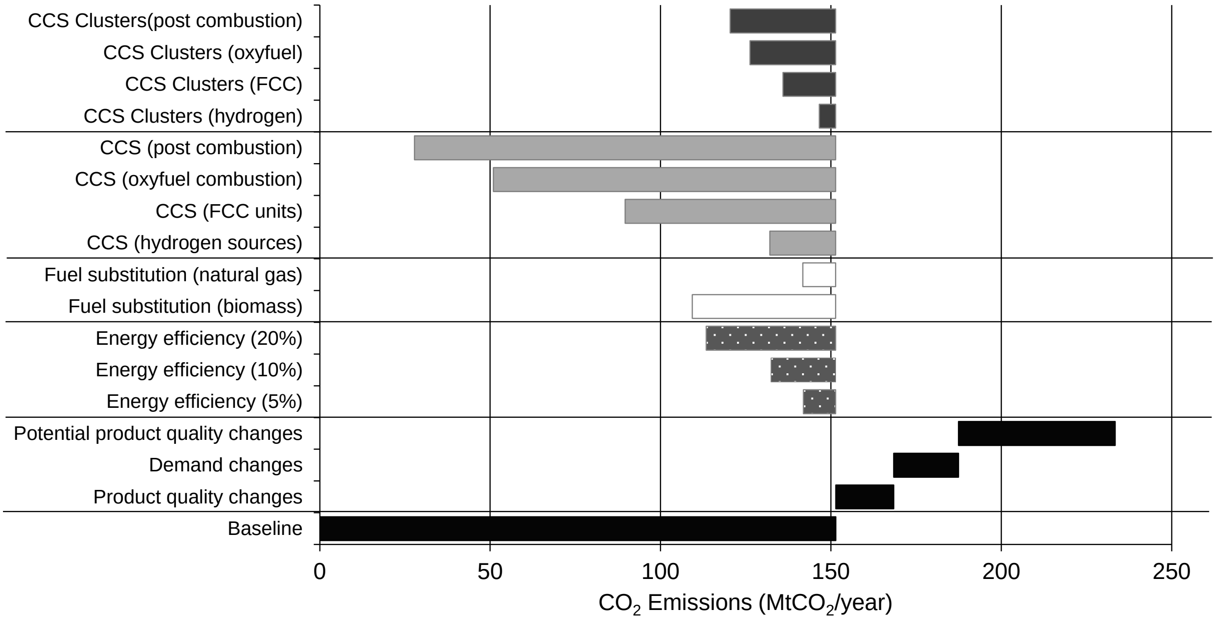

Fig. 3. Potential impacts on refinery CO_2 emissions of the assessed abatement strategies and changes in fuel demand and fuel specifications. The grey bars indicate potential reductions for the different mitigation options. The black bars, to the right, indicate potential increases in CO_2 emissions (a consequence of demand and product changes). The baseline represents the current CO_2 emissions from the European refining industry (average CO_2 emissions in 2007–2009). All CO_2 mitigation measures are scaled to represent the current European refining industry.

The assessment shows that continued energy efficiency improvements and fuel switching represent the most promising strategies for CO_2 emission reduction in the short term. However, the overall abatement potential is relatively low. Increased energy efficiency could contribute to lowering the CO_2 emissions by 10–20 MtCO_2/year by 2020 for the whole sector and an additional 20 MtCO_2/year in the longer-term if new advanced processes are installed (e.g., biodesulfurisation). The lower energy efficiency potential is perhaps pessimistic, although it is likely that it will be considerably costly to install all the energy efficiency measures.

Applying a fuel shift gives an overall abatement potential of 9.6 MtCO_2/year (Fig. 3), thereby releasing refinery liquid fuel for alternative uses. The effect on global CO_2 emissions depends on the alternative use of the released fuel. It should be noted that the released refinery liquid may replace more carbon-intensive fuels in other applications. Such fuel substitution will contribute to an additional reduction in CO_2 emissions. However, the present study focuses on petroleum refineries; the effect on the entire energy system is beyond the scope of this work.

In the longer term, another possibility would be to introduce biomass for direct use in boilers or through biomass gasification into synthetic natural gas. A gross estimate of the potential effects of replacing liquid fuel with biomass instead of natural gas indicates a CO_2 emission reduction potential of 42 MtCO_2/year (Fig. 3). Such a shift would however involve major refurbishments to current boilers.

For the petroleum refining industry to achieve more substantial reductions in CO_2 emissions in the longer term (up to 2050), implementation of CCS is necessary. The potential for CO_2 capture, if applied to all the refineries assessed in this work, is estimated to be 19–123 MtCO_2/year. The large span depends on the choice of capture technology (post-combustion or oxyfuel combustion capture) and targeted CO_2 stream (e.g. targeting only flue gases from hydrogen production or targeting a combination of flue gases). If CO_2 capture is introduced only at the refineries that are located within CO_2 clusters, the abatement potential will be significantly lower at 5–30 MtCO_2/year (Fig. 3). Of this potential, 93% is attributed to refineries with emissions that exceed 1 MtCO_2/year.

As mentioned above, each individual measure often has an influence on the potential for other measures. Thus, simply adding up the reduction potentials for all abatement strategies to calculate the total potential is not feasible. Furthermore, comparisons of current CO_2 emissions, potentials for available abatement measures, and potential future increases in CO_2 emissions (due to product quality changes, demand changes, potential product quality changes [30]) demonstrate that the trend towards increased CO_2 emissions intensity might continue to offset a significant share of the emission reductions. The potential CO_2 emission increases associated with demand and quality changes are in the range of 36–82 MtCO_2/year.

4 Discussion

The aim of this paper is to assess critically the limitations of key abatement options in the EU petroleum refining industry, with the emphasis on the technical potentials. The estimations of the CO_2 reduction potentials for the individual CO_2 abatement strategies, obviously, depend on the assumption made in the analysis. The results are based on general technical estimations and are subject to considerable uncertainty with regards to site-specific potentials. Furthermore, since not all available mitigation options could be assessed for the EU refining industry as a whole, these options were not included in the present study. For a more detailed and thorough analysis, all mitigation options should be investigated in detail, together with consideration of site-specific conditions. Nevertheless, our results indicate areas with potential to utilise adjacent energy infrastructure, and show the relative magnitude of the CO_2 reduction potential from using such infrastructure, as well as from applying on-site mitigation options.

CO_2 capture is, not surprisingly, the CO_2 abatement option with the highest CO_2 reduction potential in the long-term. However, to date, the practical experiences with CO_2 capture in the refining industry are limited. Thus, the CO_2 capture projects currently being initiated will provide valuable insights into both the technical and economic aspects associated with CO_2 capture in the refining industry. Examples of announced demonstration projects include a post-combustion capture installation connected to a new refinery CHP plant in Mongstad, Norway [76] and an oxy-combustion demonstration project of an FCC in Parana, Brazil [22]. The wide ranging estimates of the potentials for CO_2 capture presented in this paper are meant to illustrate the possible outcomes of different strategies for the implementation of CCS in the EU refining industry. The high-concentration CO_2 sources in the petroleum refining process (i.e., hydrogen production units) are generally assumed to offer the best prospects for early deployment of CCS in the oil refining industry [66, 77]. In today´s refineries, high-concentration sources typically account for a relatively small share of the total CO_2 emissions from the refining process. However, the combined effect of a continued increase in the diesel/gasoline ratio, tightening of the sulphur specifications and an increase in the CO_2 price will lead to increased utilization of hydrogen (mainly as feedstock for hydro processing units but perhaps also as a fuel in the process furnaces and boilers) and, thus, increase the share of CO_2 emissions from high-concentration sources (further analysed in [33, 77]). This development will also lead to that the use of the energy-intensive units in the refining process (e.g. FCC), which are aimed at producing gasoline, will decrease. This development has not been considered when estimating the potential for CO_2 capture from hydrogen production and FCC processing. Therefore the actual potential for CO_2 capture from hydrogen manufacturing sources may be higher than indicated and the potential for CO_2 capture from the FCC units may be lower than indicated in the results.

The upper estimate of the potential for CO_2 capture presented in this paper is based on the assumption that flue gases from all major CO_2 sources in the processes are targeted. While theoretically feasible, such a strategy would be associated with considerable costs and might also be limited by site-specific constraints (i.e., limited space available for the required infrastructure).

Several of the abatement options will rely on access to appropriate infrastructures and on integration between sectors. With respect to CCS, where the infrastructure for transportation and storage of CO_2 has not yet been developed, opportunities exist to lower the total costs of the CCS chain if efforts to develop integrated CO_2 transportation networks are coordinated across sectors and between member states.

The assessment of adjacent district heating networks is based on the distance to existing networks. However, it needs to be determined whether the capacity and demand for expanding the district heat delivery exist. It has proven difficult to obtain access to data on current district heat delivery levels from the refineries. As a consequence, the data used in the present study were retrieved from only a few refineries.

The abatement options presented above may not be comparable, and the full potential cannot be deduced by adding all the potentials. There is, for example, a conflict between energy efficiency measures and district heat delivery. If efficiency measures are implemented, less excess heat will be available for export. The potential for carbon capture may compete with excess heat delivery and energy efficiency measures due to the energy penalties associated with the capture process (i.e., oxygen separation or absorbent regeneration). Moreover, even if several abatement options are compatible, economic considerations will likely limit the number of measures employed at any single refinery.

Estimations of the potential for energy efficiency improvements and associated costs have important implications when assessing the relative roles of different abatement options. In times of high energy prices, the issue of energy efficiency profitability tends to re-emerge [78]. Bottom-up studies frequently report significant opportunities for low-cost (or negative-cost) energy efficiency improvements. However, many economists argue that analyses that show strong profitability for energy efficiency must have overlooked some real costs (but perhaps intangible) for consumers or firms, otherwise such strategies would already have been implemented [78 – 80].

As emphasised above, our estimates reflect only the technical potentials. A prerequisite for realising the potentials is a significantly higher cost for emitting CO_2 than the current price (at the time of writing, the price of emission allowances in the EU ETS has fallen to 7 €/tCO_2). The direct and indirect cost impacts of carbon trading within the EU ETS vary across sectors [81, 82]. The total cost impact for the EU refining industry, for a CO_2 price in the range of 30–40 €/tCO_2, has been estimated to correspond to less than 1% of the production value [82] or approximately 12% of the gross value added [83]. Estimates of CO_2 abatement costs also vary significantly in the literature depending on abatement option considered, regional scope, and assumptions made, such as discount rates and fossil fuel prices. Branco et al. [84] have evaluated the abatement costs for thermal energy management and fouling mitigation in Brazilian oil refineries, assuming two discount rates. The results show relatively high abatement costs of 20.2–77.3 $/t$CO_2$ for thermal energy management and 115.6–210.8 $/t$CO_2$ for fouling mitigation. Similarly, in a study of the Brazilian oil refining industry in which the impact of CO_2 taxation on the configuration of new refineries was investigated [77], new refineries were found to be relatively insensitive to the impacts of CO_2 emission pricing. These results indicate that measures to reduce emissions in new refineries would be implemented first at price levels above 100 $/t$CO_2$. In contrast, a recent study of the potential for CO_2 abatement in the EU refinery sector up to 2030 has suggested that significant emission reductions could be achieved at negative costs (the cost estimates here refer to the social cost) [85]. Stenhufvud and Holmgren [15] have also reported negative costs for a number of abatement measures in Swedish refineries.

The most straightforward way to reduce the CO_2 emissions associated with the petroleum fuel chain would, obviously, be a shift away from petroleum fuels in the end-use sectors (i.e., the transport sector), which would gradually make the petroleum refineries obsolete. A key assumption in the present work, however, is that the petroleum refining industry will continue to play a major role in providing transport fuels over the coming decades. If alternative fuels (e.g., electricity and biofuels) achieve a larger share of transport energy use or if crude oil runs out faster than expected, the refining industry will clearly be affected. Branco et al. [34] argue that the main strategies to meet uncertainties regarding feedstock and product characteristics are to increase refinery complexities and versatility, and to integrate the refining and petrochemical industries. Thus, it is reasonable to assume that the most complex refineries are those that will be most capable of adjusting to new fuel demands, which means that they will endure the longest. In addition, refineries with green profiles or highly efficient processes may also find it easier to adjust to a carbon constrained market.

In future studies, it would be interesting to expand the system borders to include the whole fuel chain, from well-to-wheel, to assess the effects of different CO_2 emission strategies on the petroleum refining process, including the production of alternative fuels.

Evaluating the CO_2 effects associated with increased use of biomass for renewable fuel production is complex and has not been included in this assessment. However, co-feeding biomass-derived feedstock with crude oil could be one way to decrease dependence on the petroleum feedstock and to reduce global CO_2 emissions. The existing FCC units and the hydro-treating units can be used for processing biomass to fuels with good fuel specifications [86, 87], but the potential for co-processing is currently limited both in terms of hydro-treating capacity and available bio-oil feedstock.

Neste Oil in Finland and Preem AB in Sweden are two petroleum refining companies that have initiated the production of renewable diesel, in addition to their regular diesel production. Preem AB has modified existing hydro-treating units for renewable diesel production, while Neste Oil has developed the NExBTL renewable diesel production technology, which has been installed at refineries in Finland and Singapore, and shortly in Rotterdam [88]. According to Concawe [30], meeting the future trend in demand related to fuel shifting and stricter fuel and environmental specifications will require an additional capacity of 774 ktH_2/year by 2020 (compared to 2005). One possible strategy to meet this demand and at the same time reduce CO_2 emissions would be to produce hydrogen through on-site gasification of biomass. A study by Johansson et al [89] has shown that 16,000 Nm^3 H_2 production from biomass gasification, as compared with steam methane reforming, could reduce emissions by 170 ktCO_2/year. This is, however, an alternative that is still under development, and further research and process modifications need to be performed before the technology is ready to be commercialised.

5 Conclusions

The present work shows that the EU petroleum refining industry has potential to reduce its CO_2 emissions considerably.

Access to infrastructures, such as district heating networks, natural gas grids, chemical industries, and possible CCS storage sites, which could facilitate CO_2 abatement, varies across countries. Refineries located along the North Sea generally have good access to such infrastructures, and thus have more alternatives for CO_2 mitigation than other locations, such as southern Europe.

It is shown that short-term mitigation options, fuel substitution, and energy efficiency measures could reduce the current CO_2 emissions by 9–20 Mt/year. A reduction of 13–80% could be achieved by implementing carbon capture. Assuming that carbon capture will be implemented only in those areas with many large CO_2 emission sources, the potential of CO_2 emission reduction decreases to 5–30%.

The expected trends of stricter fuel quality standards, changes in fuel demand, and increased indirect energy demand (e.g., hydrogen production) will likely offset some of the potential for CO_2 emission reduction.

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Fig.1. Output of petroleum products in ktoe/year (grey bars) and internal energy consumption as share of total output given in percent (black line). Data source: [32].

Fig. 2. Geographical distribution of refineries with CO_2 emissions >1 Mt/year in relation to district heating systems (DH), chemical clusters (CC), and natural gas grids (NG). The numbering indicates the combination of different adjacent infrastructures. Possible CO_2 storage sites are represented by grey lines. Potential capture clusters, regions where emissions from large stationary point sources (including also emissions from power plants and pulp and paper plants) exceed 20 $MtCO_2$ annually, are highlighted in grey. This map includes the intellectual property of the European National Mapping and Cadastral agencies and is licensed on behalf of these agencies by EuroGeographics.

Fig. 3. Potential increases in CO_2 emissions (a consequence of demand and product changes) and the potential for CO_2 emission reductions from different CO_2 abatement strategies. The black bars, to the left, indicate potential increases in CO_2 emissions. The patterned bars indicate potential reductions for the different mitigation options. The baseline represents the current CO_2 emissions from the European refining industry (average CO_2 emissions in 2007–2009). All CO_2 mitigation measures are scaled to represent the current European refining industry.

Table1. Refinery configurations [10, 12].

Simple and Base oil refinery	The production includes no conversion units, which makes these refineries limited to the production of heavy fuel oil.
Configuration 1	The simplest type of oil refinery. These refineries are equipped with a distillation unit, naphtha reformer, and some necessary treatment facility.
Configuration 2	Can convert fuel oil to a more valuable fuel by adding a vacuum distillate unit and a catalytic cracker to the hydro process above.
Configuration 3	Has a hydro cracker, which maximises the production of gasoline and middle distillates and allows the production of high-quality diesel [42].
Configuration 4	Has both hydro cracking and catalytic cracking units. Some refineries have an IGCC unit, which converts solids and heavy fuels to power, co-generation steam, and lighter products. Eleven refineries in the EU-27 countries have a coker unit, which reduces heavy fuel oil and produces a low-value product, coke.

Table 2. Key characteristics of the petroleum refinery stock in Europe [27].

	Number of refineries	**Crude oil [Mb/d]**	**CO_2 emissions[Mt/year]**	**Divided by complexity**			
				Base+Conf. 1	Conf. 2	Conf. 3	Conf. 4
EU plus Norway	114	16.07	154.51	34	45	14	18

Table 3. Energy saving potentials for a selection of measures described in the literature.

	Szklo & Schaeffer [9]	**Alsema [54]**	**Petrick & Pellegrino [53]**	**Worrell and Galitsky [10]**
Heat integration and waste heat recovery	10%[a]	6%[b]	5% (20–40%)[c]	10–30%[d]
Fouling mitigation	2%	2%	2%	0.7–3.4%[e]
Advanced process control	2%	2.5%		2–18%
Combustion efficiency improvements			7%	13–33%[f]
Advanced turbine systems/Co-generation			2 %	
Thermal cracking	17%	18%	5%	
Membrane technology[g]	-	-	-	-
Pumps	1%[h]			2–17%[j]
Biodesulfurisation	70–80%[i]	4.4%	2%	
Oxidative desulfurisation process	40%[k]			

(ODP)		
Catalytic distillation (CD) process	62%[l]	
Advanced catalyst for Fluid Catalytic Cracker (FCC) and hydroprocessing		15%

[a] Includes: use of waste heat in absorption refrigeration systems; use of waste heat to pre-heat feeds; heat and/or mass (water and hydrogen) integration using Pinch techniques; improvement of furnace efficiencies in combination with computer-controlled combustion; direct feeding of "intermediary products" to process without cooling or storage; use of heat pumps; decreased film temperature and increased turbulence on heat transfer surfaces; insulation of buildings and process units; and adoption of steam management.
[b] Includes: improved heat management and waste heat recovery; and process integration and cross-industry optimisation.
[c] This number is based on energy savings reported from several pinch analyses [53].
[d] Based on several pinch analyses conducted at different refineries.
[e] The second number is from [55], translated into percentage of the specific energy consumption of Brazilian refineries [9]
[f] Includes: improved process control; reduced flue gas quality; improved insulation; boiler maintenance, and flue gas heat recovery.
[g] The actual savings achieved with membrane separation are unclear. None of the studies found this option to be very promising. Petrick and Pellegrino [53] do not even mention this option.
[h] Percentage of electricity consumption.
[i] Reported by Linguist and Pacheco [53], in [9]. Percentage relative to conventional hydrodesulfurisation.
[j] Percentage of energy consumption by pumps.
[k] Percentage relative to conventional hydrodesulfurisation.
[l] Percentage relative to conventional hydrodesulfurisation.

Table 4. Breakdown of CO_2 emissions from a petroleum refinery

	Fraction of CO_2 emissions
All sources[a]:	
Furnaces and boilers	65%
Regeneration of catalytic cracker catalyst	16%
Power (55% imported)	13%
Other sources	6%
Major isolated sources[b]:	
FCC	20%–45%
Hydrogen manufacture	5%–20%

[a] Based on [67]. Other emission sources include flaring, methane steam reforming, effluent processing, and incineration.
[b] Based on [17, 22, 63]

Table 5. Characteristics of the capture options considered in the assessment.

Targeted flue gas streams	CO_2 concentration in gas stream[d] (% by gas volume)	Capture technology	Cost per tonne of CO_2 captured (€/t)	Average recovery rate (% of plants total CO_2 emission)
Furnaces and boilers[a]	3–13	Oxyfuel combustion	~30	65
CHP plant + FCC[b]		Post-combustion	~45	80
FCC[c]	10–20	Post-combustion	-[d]	40
		Oxyfuel combustion	-[d]	40
Hydrogen manufacture[e]	20–99	Post-combustion	~24 - 53	12.5
CHP plant + FCC + gas turbine + two Combined stacks[f]	4–13	Post-combustion	~90–120	40

[a] Estimations based on [68,69].
b Estimations based on [70].
[c] Estimations based on [63].
[d] No monetary cost estimates presented. The capture cost is estimated to be 45% lower in the oxyfiring case than in the post-combustion case.
[e] Estimations based on [15,71].
[f] Estimations based on[17].

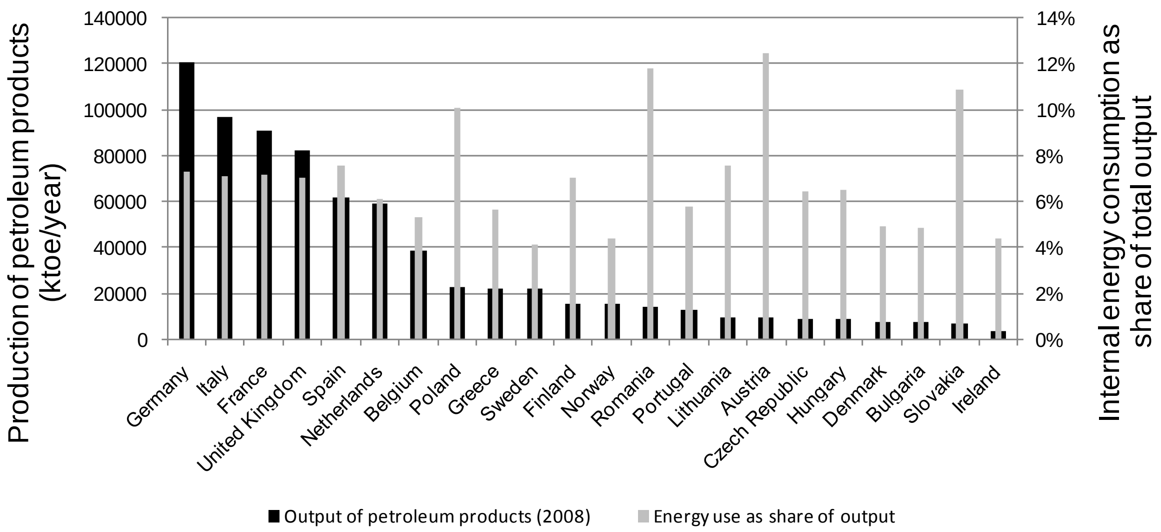

Figure 2 in colour for online publication:

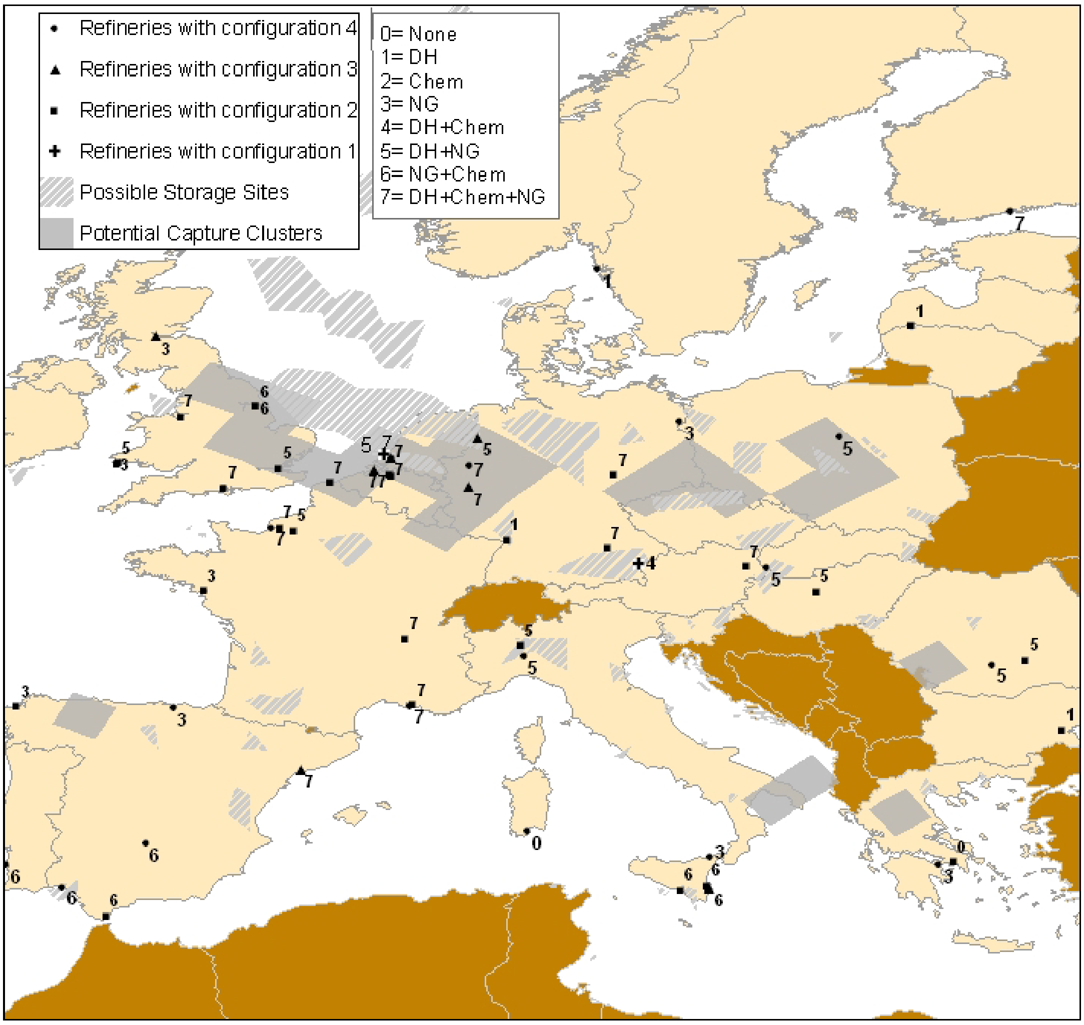

Figure 2 in black-and-white for printing purposes: