POTENTIAL AND COSTS FOR CO_2 MITIGATION OPTIONS FOR MINERAL OIL REFINERIES IN EU-28 FOR 2050

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Abstract

In February 2011, the European Council reconfirmed the EU objective of mitigating greenhouse gas emissions by 80 – 95 % until 2050 compared to1990 to prevent drastic climate change. To reach that target, all sectors of the society are to put an effort into reducing their emission level. The European petroleum refining industry accounts for 3.4 % of GHG emissions in all industry activities and 7.2 % in the energy production and use sector. In the verified emissions table (VET) of the EU emissions trading system (EU ETS), we find 130 installations with total emissions of about 130 Mt in 2015 (European Commission 2015). This makes up for about one quarter of emissions accounted for by industrial activities in the EU ETS. At present, comprehensive analysis on energy demand, CO_2 emissions, CO_2 mitigation potential and costs using energy saving options have not been conducted at plant- and energy carrier-level for this important subsector. Here we present an approach to model the energy demand and CO_2 emissions for the European refinery sector based on a plant level investigation. In a scenario analysis, we investigate capacity development and saving potential. Moreover, we show technical and economic potential of energy saving and CO_2 mitigation in consideration of the energy saving options.

The site-level calculation of energy demand and CO_2 emissions by energy carrier showed that there were roughly 49.0 million tonnes of oil equivalent consumed and about 130 million tonnes of CO_2 emitted in 2015 by the EU refinery sector. From the scenario analysis, it was observed that energy demand and CO_2 emission may decline by around 16 % by 2050 in the reference scenario, compared to the levels in 2015. In addition to the reference scenario, a policy scenario was developed using inputs based on a roadmap in European Commission (2011). Under the conditions of this scenario, 53 % of further CO_2 mitigation could be achieved by 2050 compared to the reference scenario. The reviewed energy saving options can cause about 7-10 % of additional potential energy savings and CO_2 mitigation of the refineries under different diffusion conditions. The methodology of site-speicifc estimation and projection of energy demand and emissions by refinery category seem plausible enough, given the good match of top-down and bottom-up values on an overall level.

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1. Introduction

The European Union (EU) has reconfirmed the necessity to mitigate the greenhouse gas (GHG) emission by 80-90 % in comparison to the emission level in 1990 to keep the temperature rise of the globe below 2 °C (European Commission 2011). To achieve the goal of reducing GHG emission, it is important that all economic sectors contribute. The refinery sector in EU accounts for 3.4 % of GHG emissions in all industry activities and 7.2 % in the energy production and use from 2007-2009 (Barthe et al. 2015). Furthermore, the sector accounted for about 25% of the industrial emission in the EU ETS in 2015. While both total CO_2 emissions and fossil fuel-related emissions in EU have declined since 1990, CO_2 emissions by the refineries in EU have increased by approximately 17 % driven by the increase in demand of oil products especially from transportation sector (Johansson et al. 2012). Although the oil demands have been replaced partially by renewable energy, the oil products are anticipated to keep playing a major role in the transportation, industry, and power and heating sectors (Europia 2010). Therefore, to achieve the EU's goal to realize the low-carbon future, it is important to study the emission profile of the refinery sector and its projection in the future in different scenarios as well as identifying mitigation options and their potential and costs.

There are numerous studies regarding the potential and costs for refineries' CO_2 mitigation options. Bernstein (2008) investigated on mitigation options for the refinery sector such as more energy efficient electrical equipment, using wasted heat and power, substituting fuels with less carbon-intensive alternatives for the near future and applying carbon capture and storage.

Worrell and Galitsky (2004) investigated the energy saving potential for the U.S. refineries and depicted technologies applicable for each process. They found that there is a potential 10 - 20 % energy efficiency improvement in most of the petroleum refineries in the U.S. Chan et al. (2015) studied energy saving options (ESOs) for the refinery sector in Europe in different scenarios: A business as usual (BAU) scenario, a technical scenario and an economic scenario. According to the study, there were 10.6 million tonne of oil equivalent (Mtoe) (25% saving) of energy saving potential in 2030 and 8.3 Mtoe (23.0 % saving) in 2050 in the technical scenario in comparison to the business as usual (BAU) scenario whereas 1.7 Mtoe (4.5 % saving) in 2030 and 3.1 Mtoe (9.0 % saving) in 2050 were suggested with respect to the BAU scenario in the economic scenario. Although these two studies showed great CO_2 mitigation potential of the refinery sector, individual characteristics of each refinery were not considered. Instead, the whole sector was represented by a generic refinery.

On plant level, Johansson et al. (2012) studied the effect of adjacent infrastructures such as district heating networks, natural gas grids, neighboring industries, and CO_2 transport and storage systems for the EU refinery sector. The study showed a reduction potential of 6 - 26 % for the short-term and 5 - 80 % for the long-term by carbon capture storage. The study focused on future technologies as mitigation options, but the currently available technology was not the focus of the study.

At present, a comprehensive study on energy demand, CO_2 emissions, CO_2 mitigation potential and costs using ESOs has not been conducted at plant- and energy carrier-level for the EU refinery sector. Hence a model to investigate the energy demand and CO_2 emissions for the European refinery sector at the plant level is presented in this study. Furthermore, in the scenario analysis, CO_2 mitigation potential and costs are investigated.

The overall aim of the paper is to estimate the status-quo of the refineries in terms of CO_2 emissions and energy demand on plant level and how they could change in the future until 2050 in EU-28 under different scenarios. Furthermore, the study focuses on identifying potential and costs for CO_2 mitigation options with technical and economic conditions taken into account.

Particularly, to calculate the CO_2 emissions on site level based on energy demand, the study focuses on finding the correlations between processes of refineries and energy consumption by energy carrier and the consequent CO_2 emissions. By employing a categorization model based on process configuration, each refinery is assigned to a category with corresponding product slates (relative quantities of petroleum products). Moreover, the paper identifies main drivers for the production of refinery products and develops a projection of the total energy demand and the total CO_2 emissions of the European refineries for 2050 under different scenarios. Finally, the study seeks to show potential and costs of ESOs under differing diffusion assumptions.

Based on the aims of the study, the objectives of the study can be expressed by the following research questions:

1. What is EU refineries' status-quo in terms of production, energy demand and CO_2 emission on site level?
2. How could the energy demand and CO_2 emission of the EU refineries change, driven by the production projection until 2050 under various scenario?
3. What are the potential and costs for the EU refineries to reduce CO_2 emissions by employing energy saving options under various diffusion conditions?

1.1. Refinery Process

Refineries are large industry complexes that process crude oil comprising of various hydrocarbons into products ranging from heavy fuel oils to refinery gas (Worrell, Galitsky 2004). Different processes are utilized with various technical configurations to achieve the desired production with required qualities.

Figure 1-1 presents an overview of a common refinery structure with their configuration and the typical products. Based on purposes, the refining processes can be grouped into separating, cracking, restructuring, treating, and blending. During the separation process, the crude oil is first distilled and collected by their boiling point differences. The relevant processes are a crude distillate unit (CDU) and a vacuum distillate unit (VDU).

In the cracking process, the streams are converted into smaller hydrocarbons (e.g. gasoline, diesel) which have more values. The cracking process units include a fluid catalytic cracking unit (FCCU), a hydro cracking unit (HCU), a thermal cracking unit (THU), a visbreaker unit (VB) and a coking unit (DK).

The restructuring process modifies the quality of the products such as octane number of gasoline, which happens in a reformer unit (RF)

To eliminate the impurities such as sulfur out of the products, the treating process is included in refineries such as a desulfurization unit (DSU).

Lastly, the product streams are mixed to give desired product slates (Morrow III et al. 2013). Other than the major processes, side processes include desalting units for crude oils, steam reforming units (hydrogen production), power and steam production units and asphalt production units (Worrell, Galitsky 2004).

From the refining processes, the typical products that are manufactured are refinery fuel gas, LPG, gasoline, aviation fuel, heating oils, lubricants, heavy fuel oils and bitumen (Worrell, Galitsky 2004). The products are consumed mostly in transportation, industry, and heating & power sector (Chan et al. 2015).

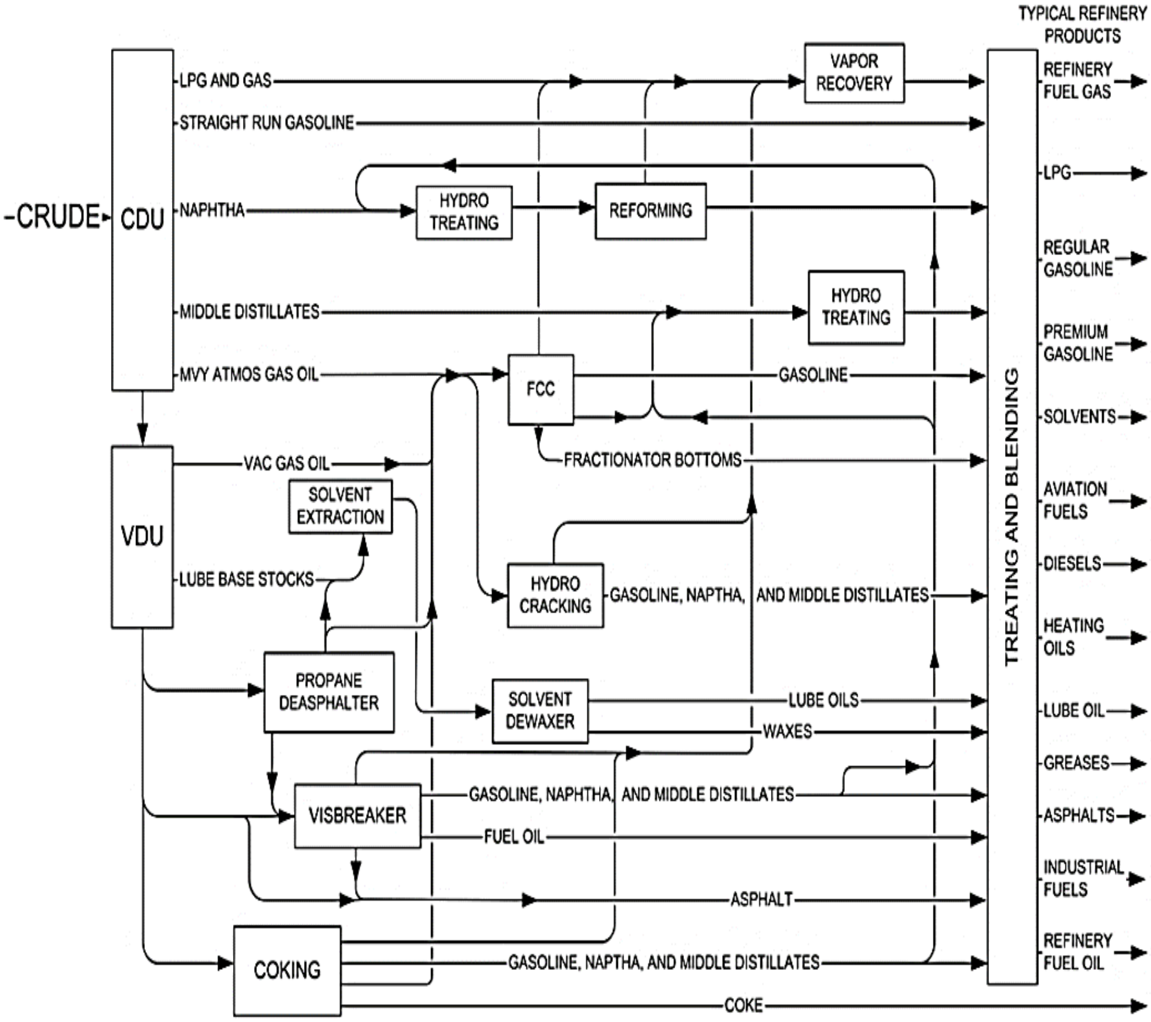

Figure 1-1. Overall depiction of the refining processes and the typical products (Worrell, Galitsky 2004).

1.2. European Refinery Sector

There are currently 104 refineries with the total capacity of around 700 Mt crude oil/y (based on the CDU capacity) that are operating in EU-28 according to an annual survery carried out by the Oil and Gas Journal (2016).

In 2014, 42.5 Mtoe of energy was consumed by the refineries in EU-28 (EUROSTAT 2017b). These data show that Germany and Spain have the highest energy demands (7.0 Mtoe, 6.6 Mtoe respectively) which are about 16 % each of the total energy consumption in the EU refinery sector. Next in line are the U.K and Italy which consumed about 4.1 Mtoe each which are about 10 % of the total energy demand.

In the verified emissions table (VET) of the EU emissions trading system (EU ETS), we find 130 installations with total emissions of about 130 Mt in 2015 (European Commission 2015). This makes up for about one quarter of emissions accounted for by industrial activities in the EU ETS.

2. Methodology

The methodology of this paper is based on the FORECAST methodology concept, developed by Fraunhofer ISI. The FORECAST modelling develops long-term scenarios for future energy demand. By employing a bottom-up approach considering the dynamics of technologies and socio-economic drivers (main drivers) (e.g., gross value added, energy demand), the model estimates energy saving potential and GHG reduction potential (FORECAST 2017). Figure 2-1 describes the research process that was adopted for this paper. First, site-level data was collected in terms of process capacities, utilization rates, energy demand, CO_2 emission and products by category of refinery. Second, the main drivers were correlated to each product of refineries. Driven by their changes in the future, scenarios for change of productions, energy demands and CO_2 emissions until 2050 were developed. Finally, by considering diffusion of energy saving options for the refineries, energy saving and consequent GHG mitigation potential were estimated.

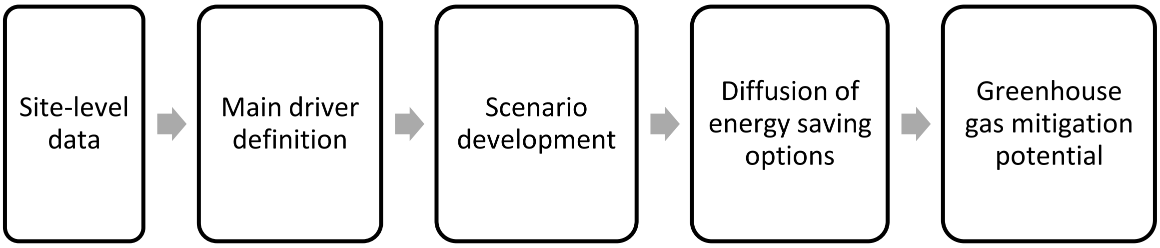

Figure 2-1. Research methodology based on FORECAST bottom-up approach (Kim 2017).

2.1. Site-level data

Capacity and utilization rate

Based on Oil and Gas Journal (2016), 104 refineries existed in EU-28 with the total CDU capacity of around 700 Mt crude oil/y. Among EU-28, some countries did not have refineries and several refineries were found to be non-operational or to be specially used for specific products (without CDU) (Oil and Gas Journal 2016). Therefore, in this research, the total of 98 refineries were investigated in 22 countries in EU which had a CDU capacity of approximately 690 Mt crude oil/y (Cyprus, Estonia, Latvia, Luxemburg, Malta, Slovenia were excluded.).

Utilization rates show the actual operation of the capacities in the refineries. Since the utilization rates of the refineries were not publicly available, the values were estimated based on BP (2016) (see Table 2-1). Since the site-specific value was not available, country-specific values were employed. Moreover, the CDU utilization rates were applied to other processes assuming the same value for each process.

Table 2-1.Capacity and throughputs and calculated utilization rates by country.

Country	Capacity (1000 barrel per day)	Throughput (1000 barrel per day)	Utilization rate (%)
Germany	2032.0	1876.0	92.0
Italy	1915.0	1341.0	70.0
Spain	1546.0	1304.0	84.0
France	1375.0	1151.0	84.0
UK	1337.0	1136.0	85.0
Netherlands	1293.0	1138.0	88.0
Belgium	776.0	644.0	83.0
Poland	581.0	532.0	92.0
Greece	498.0	433.0	87.0
Sweden	436.0	401.0	92.0
Portugal	306.0	281.0	92.0
Finland	261.0	197.0	75.0
Romania	246.0	208.0	85.0
Lithuania	241.0	174.0	72.0
Bulgaria	195.0	121.0	62.0
Austria	193.0	173.0	90.0
Denmark	180.0	147.0	82.0

Country	Capacity (1000 barrel per day)	Throughput (1000 barrel per day)	Utilization rate (%)
Hungary	165.0	130.0	79.0
Slovakia	122.0	119.0	98.0
Ireland	75.0	68.0	91.0

Note: Based on (BP 2016).

Energy intensity of refinery process

Energy intensities indicate the amount of energy required to process a unit ton of product stream (Lukach et al. 2015). Worrell and Galitsky (2004) estimated energy balance for the U.S refineries, which we used to calculate the process specific energy consumptions. Due to limited data availability, we assume that the process technology applied in the EU-28's refineries is similar to those in the U.S.

Table 2-2 shows the summarized energy intensity values per process calculated based on Worrell and Galitsky (2004), which was used for the modelling in this study. For the calculation, steam generation percentage from cogeneration was assumed to be 52 % based on Irimescu, Lelea (2010). Several processes such as desalter, deasphalting units, aromatic units, sulfur units and other auxiliary units were not considered in this study due to the negligible contribution to the final energy use (Worrell and Galitsky 2004).

Table 2-2. Energy intensity of the refinery processes by energy carrier.

Process	Fuel	Steam	Electricity	Energy intensity (toe/t)
Crude distillate unit	49 %	48 %	3 %	0.025
Vacuum distillate unit	38 %	60 %	2 %	0.023
Thermal cracking unit	90 %	-16 %[a]	26 %	0.024
Fluid catalytic cracking unit	74 %	0 %	26 %	0.014
Hydrocracking unit	45 %	35 %	20 %	0.056
Reformer unit	55 %	40 %	5 %	0.059
Desulfurization unit	35 %	54 %	11 %	0.037
Alkylation unit	6 %	87 %	7 %	0.102
Asphalt unit	94 %	0 %	6 %	0.041
Isomerization unit	60 %	39 %	1 %	0.136
Lubricant unit	89 %	4 %	7 %	0.267
Hydrogen unit	98 %	0 %	2 %	0.085

Note. [a] Thermal cracking produces steam as by-product therefore, it shows the negative value of steam ratio. Based on Worrell and Galitsky (2004).

Energy consumption calculation

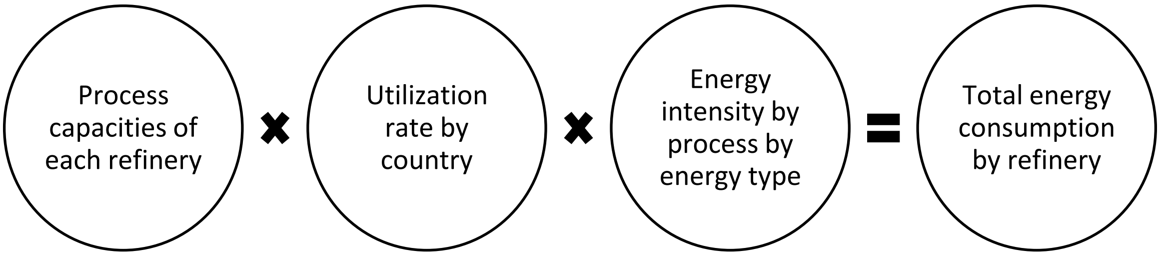

Figure 2-2. Methodology of the energy consumption calculation by each refinery site (Kim 2017).

The process capacities of the refineries in EU-28 from Oil and Gas Journal (2016) were multiplied with the utilization rate of the refineries by country to consider the actual throughputs (Figure 2-2). To account for the energy consumption for each process, specific energy consumption by process and energy types in Table 2-2 were used. By multiplying the energy intensity values with the calculated throughput by process, the energy consumption per process (and type, i.e. steam, direct fuel and electricity) was obtained.

Fuel structures and CO_2 intensity

Choice of energy carrier is most relevant for the resulting emssions intensity of the plant, as emission factors can vary significantly. Table 2-3 shows the CO_2 intensity of the refinery energy carriers according to Reinaud (2005) and Fleiter et al. (2012).

Table 2-3. CO_2 intensity of the refinery energy carriers.

Energy carriers	CO_2 Intensity (tCO_2/ toe)
Refinery Gas	3.236
Natural Gas	2.345
Petroleum Coke	4.220
Diesel Oil	3.098
Residual Fuel Oil	2.793
Electricity[a]	7.227

Note. [a] Based on generation mix from Germany in 2050. Depending on the generation mix (comprising of fossil fuel , renewable energy, nuclear power, and natural gas, CO_2 intensity can vary. Adapted from Reinaud (2005) and Fleiter et al. (2012).

These CO_2 intensities, however, could not be directly applied to the energy intensity values due to the lack of specific energy carrier information. Therefore, fuel structure of refineries in each European country was obtained from EUROSTAT (2017b). Due to the lack of information about the fuel composition for steam generation, It was assumed that the energy demand of each refinery from fuel and steam combined came from the same energy carrier ratio data from EUROSTAT (2017b) (Table 2-4).

Table 2-4. The fuel structure of the refineries in the European country in 2014.

Country	Refinery gas	Total fuel oil	Petroleum coke	Other Oil Products	Natural gas	Total
European Union (28 countries)	58.042 %	8.704 %	10.650 %	3.385 %	19.219 %	100.000 %
Belgium	57.255 %	2.206 %	14.912 %	0.000 %	25.627 %	100.000 %
Bulgaria	67.517 %	5.626 %	19.627 %	0.000 %	7.229 %	100.000 %
Czech Republic	44.944 %	0.000 %	0.000 %	26.779 %	28.277 %	100.000 %
Denmark	97.186 %	2.814 %	0.000 %	0.000 %	0.000 %	100.000 %
Germany	56.561 %	13.176 %	7.135 %	4.808 %	18.321 %	100.000 %
Ireland	55.310 %	0.000 %	0.000 %	44.690 %	0.000 %	100.000 %
Greece	46.255 %	31.110 %	21.127 %	1.508 %	0.000 %	100.000 %
Spain	74.789 %	2.890 %	1.984 %	0.517 %	19.820 %	100.000 %
France	46.697 %	5.373 %	13.618 %	2.558 %	31.755 %	100.000 %
Croatia	55.970 %	19.235 %	3.687 %	0.000 %	21.108 %	100.000 %

Country	Refinery gas	Total fuel oil	Petroleum coke	Other Oil Products	Natural gas	Total
Italy	61.977 %	7.172 %	21.578 %	0.035 %	9.237 %	100.000 %
Lithuania	66.888 %	14.957 %	18.069 %	0.000 %	0.086 %	100.000 %
Hungary	50.588 %	8.251 %	11.729 %	16.335 %	13.097 %	100.000 %
Netherlands	57.758 %	0.165 %	8.920 %	0.656 %	32.502 %	100.000 %
Austria	34.668 %	31.743 %	5.750 %	0.000 %	27.839 %	100.000 %
Poland	21.115 %	29.586 %	0.000 %	1.311 %	47.988 %	100.000 %
Portugal	2.882 %	11.995 %	0.000 %	67.943 %	17.180 %	100.000 %
Romania	65.924 %	0.235 %	12.481 %	0.000 %	21.360 %	100.000 %
Slovakia	70.764 %	0.000 %	6.843 %	0.000 %	22.393 %	100.000 %
Finland	52.211 %	4.902 %	12.021 %	1.245 %	29.621 %	100.000 %
Sweden	90.089 %	2.730 %	5.215 %	0.000 %	1.966 %	100.000 %
United Kingdom	64.697 %	4.894 %	27.812 %	0.000 %	2.597 %	100.000 %

Note. It was assumed that fuel oil consisted of residual fuel oil. Other oil products assumed to be as CO_2 intensive as diesel. Adapted from EUROSTAT (2017b).

CO_2 emission calculation

Site-specific CO_2 emissions were calculated based on the energy demand calculation. Figure 2-3 depicts the approach for the calculation of CO_2 emission on site-level by energy carriers.

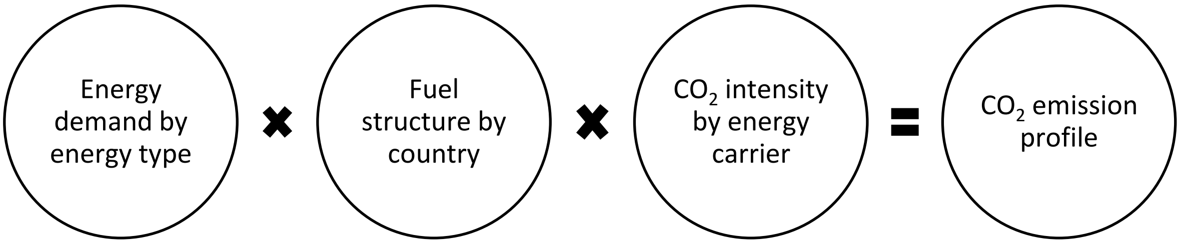

Figure 2-3. Methodology for the CO_2 emission calculation on site-level using the energy demands and the CO_2 intensities by energy carriers (Kim 2017).

The calculated energy demand was first broken down energy carriers using the fuel structures of the refineries, multiplied by the CO_2 intensity per energy carrier for each country.
8 % of steam and 73 % of electricity demand of the refineries were assumed to be purchased from providers as they were assumed by Worrell and Galitsky (2004). CO_2 emissions caused by the purchased energy carriers were not taken into account for the calculation.

Categorization

Depending on the crude oil sources, desired product slates, their sulfur contents and refineries' own strategy in the market, the configuration of the refinery processes, energy demand of the plants and products can vary. Nevertheless, similarities can be found in terms of processes they use (Reinaud 2005). These similarities were condensed into categories based on Reinaud (2005) (Table 2-5). The main purpose is to classify refineries based on their process configuration giving information about the refineries' product slates, hence retaining a large degree of detail while reducing the data complexity considerably. Major refinery processes (CDU, RF, DSU, FCCU, HCU) were selected as criteria to determine the categories since these processes influence the product slates and their flexibility the most.

Table 2-5. The adopted categories of the refineries and their main processes with short descriptions.

Categories	Process units	Characteristics
Complex 1	CDU +RF +DSU	CDU, re-structuring units (RF), treatment units (DSU) are used as primary processes. The quality of the products is determined by the quality crude oil source.
Complex 2	CDU +RF +DSU +FCCU	FCC units are equipped additionally to the complex 1 type, which is optimized for maximizing the gasoline production.
Complex 3	CDU +RF +DSU +HCU	HCU units are added to complex 1 type, which makes it more energy intensive and expensive than complex 2. It is set up for producing good quality of diesel at a higher share.
Complex 4	CDU +RF +DSU +HCU +FCCU	Both FCC and HCU units are added to the complex 1. It is featured by its flexibility of product slate changes on demand. Generally, the gasoline/diesel ratio is in between complex 2 and complex 3.

Note. CDU- Crude distillate unit, RF- Reformer, DSU- Desulfurization unit, VDU- Vacuum distillate unit, FCCU- Fluid catalytic cracking unit, HCU- Hydro cracking unit. Adapted from Reinaud (2005).

The different types of refineries are able to produce different product slates (example given in Table 2-6). Overall, Complex 1 produces the highest share of heavy fuel oil and naphtha. Complex 2 and Complex 3 produce the most of gasoline and diesel respectively. Complex 4 has the production level of diesel and gasoline in between Complex 2 and Complex 3.

Furthermore, the productions were differentiated by the geographic regions. Countries in each region are (Reinaud 2005):

1. North Western Europe: Austria, Belgium, Denmark, Finland, France, Germany, Ireland, Netherlands, Sweden, the U.K
2. Mediterranean Europe: Greece, Italy, Portugal, Spain
3. Central Europe: Bulgaria, Croatia, Czech Republic, Hungary, Lithuania, Poland, Romania, Slovakia

Table 2-6. Product slate by complex in North West Europe.

North West Europe	Complex 1	Complex 2	Complex3	Complex 4
Gasoline	13.63	32.37	26.77	27.61
Diesel	23.63	27.19	37.02	33.23
LS HFO[a]	29.76	0.00	16.10	0.00
HS HFO[b]	0.00	0.00	0.00	10.34
LS bunker fuel[c]	0.00	10.85	0.00	0.00
HS bunker fuel[d]	0.00	0.00	0.00	0.00
Heating Oil	8.83	9.18	3.10	6.02
Naphtha	14.49	8.40	5.07	9.46
Jet A1	6.27	7.21	7.00	7.14
LPG	1.43	2.29	2.51	3.55

North West Europe	Complex 1	Complex 2	Complex3	Complex 4
Bitumen	1.88	2.14	2.07	2.12
Sulfur	0.08	0.37	0.36	0.54
Coke	0.00	0.00	0.00	0.00
Total	100.00	100.00	100.00	100.00

Note. [a] low sulfur heavy fuel oil. [b] high sulfur heavy fuel oil. [c] low sulfur bunker fuel. [d] high sulfur bunker fuel. The unit for the values are relative production (2015=100). Adopted from Reinaud (2005).

2.2. Scenario development

With the base year energy demand and the CO_2 emission profile of the European refineries, different scenarios were developed, consisting of projections of the CO_2 emission and the energy demand until 2050 under differing assumptions of demand for refinery products. The projections were driven by the production of different end-uses, assuming correlations between these main drivers and the mineral oil productions. Two scenarios were developed in this paper: A reference scenario and a policy scenario.

Figure 2-4 shows the scenario development methodology employed in this study.

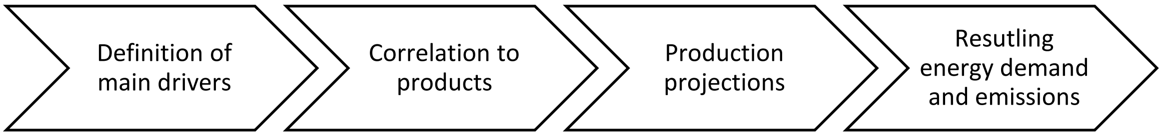

Figure 2-4. Description of the projection and scenario development process (Kim 2017).

First, the main drivers were defined and correlated to the refinery products. Using the correlations, equations were formulated for the projection of the production until 2050 on site-level. Based on the production projections, energy demand and CO_2 emission were developed for the reference scenario. Furthermore, the policy scenario was developed by employing politically influenced drivers as inputs.

In the following sections, each step of the methodology is described in detail along with the different assumptions for the defined scenarios.

Main driver and correlations to refinery products

Refinery products are used in different economic sectors. In Europe, refinery products are consumed mainly in three sectors according to Chan et al. (2015): The industry sector, the heating and power sector, and the transport sector. These main uses in economic sectors comprise of different main drivers. Main drivers are socio-economic factors functioning as indicators for the future society including diesel demand from transportation sector, for example, gross value added (GVA) from industries and fuel substitution (Herbst et al. 2012). Using the assigned mains uses of the products (Industry, transportation, heating& power), the main drivers of the refinery products were specified, based on European reference scenario in Vita et al. (2016).

Main drivers of transport were comprised of energy demand in total and the fuel mix ratio between gasoline, diesel and kerosene (Vita et al. 2016). Furthermore, the energy demand by inland navigation based on Vita et al. (2016) and fuel substitution in the inland navigation by natural gas were taken into account (Lloyd's Register Marine, UCL Energy Institute 2014). The latter implied that oil inland navigation fuel could be replaced by LNG by around 20 % from 2010 to 2030. In this paper, 1 % annual LNG penetration was assumed from 2015 to 2050. Using the average fuel composition changes in Vita et al. (2016), the energy demand fuel mix from 2010-2050 was applied divided into gasoline, diesel and kerosene demand. Biofuels, electricity, gaseous, and hydrogen represent alternative fuels that are used in the transportation sector, replacing conventional oil products. Overall, according to Vita et al. (2016), although transportation activity was anticipated to rise, due to the enhancement in energy efficiency, the total energy demand would probably not change significantly. Moreover, the shift from gasoline to diesel cars in EU might happen resulting in gasoline demand decrease whereas diesel may keep a similar level (Vita et al. 2016). Overall, the study suggested that alternative fuels such as biofuels, electricity, hydrogen and gas were anticipated to have more portion in the energy mix in the future.

For the industry sector, since the chemical industry uses refinery products as feedstock for their manufacturing process, the economic activity of chemical industry was used as the main driver. Elasticity of chemical industry sector was included as a decoupling factor to account for the possible consumption change in the chemical sector. The value was calculated from historic values from EUROSTAT (2017a) estimated as the refinery product consumption change by chemical industry, divided by the GVA change of the chemical industry. The value was estimated as European average value (2005-2014) and applied to all EU countries.

Finally, main drivers of heating and power sector comprised of energy demand by energy carrier in the residential sector (Vita et al. 2016). From the study, oil demand in the residential energy mix in EU-28 was shown to be around 25 % in 2010, which could linearly decrease to be 15 % by 2050 due to fuel substitution by renewable energies and natural gas (Vita et al. 2016). This fuel composition was applied at EU-level.

The main drivers specified were correlated to the refinery products to investigate the impact of the main drivers on refineries' production change and the consequent energy demand, and the CO_2 emission. Table 2-7 summarizes the refinery products and the corresponding main use and main drivers by country. Table 2-8 shows the example of main drivers used for the reference scenario for Austria. In the first section, the annual changes of the main drivers for the refinery products are shown in four different time periods, calculated using compound annual growth rates based on data in (Vita et al. 2016). In the second section, the assumed elasticity value for chemical industry and the fuel substitution for the inland navigation activity are displayed. In the following chapter, using these correlations, production projection equations are introduced.

Table 2-7. Detailed correlation of main drivers with each refinery product.

Products	Main use	Main driver
LPG	Industry, heating and power	Gross value added (GVA) from chemical industry, elasticity of chemical industry Energy demand and fuel mix of residential sector
Naphtha	Industry	GVA of chemical industry, elasticity of chemical industry
Gasoline	Transportation	Gasoline demand from transportation sector
Jet A1	Transportation	Kerosene demand from transportation sector
Diesel	Transportation	Diesel demand from transportation sector
Heating Oil	Heating & power	Energy demand and fuel mix of residential sector
HFO (Low sulfur and high sulfur)	Heating & power	Energy demand and fuel mix of residential sector
Bunker (Low sulfur and high sulfur)	Transportation	Energy demand from inland navigation, fuel substitution by LNG
Bitumen, sulfur, coke	Industry	Proportional production linked to gasoline

Note. Developed based on main uses from Chan et al. (2015) and specific drivers from Vita et al. (2016).

Table 2-8. Main driver of Austria for the reference scenario.

Austria	Annual Change (%) (CAGR[a])			
	10-'20	20-'30	30-'40	40-'50
Residential energy demand	-1.5	-1.5	-1.3	-1.8
Chemical industry value added	1.8	0.9	1.1	0.6
Energy demand from road transport gasoline consuming activity	-3.6	-2.1	0.0	-0.2
Energy demand from road transport diesel consuming activity	-0.5	-0.4	0.0	-0.2
Energy demand from aviation activity	0.2	0.2	0.6	0.4
Energy demand from inland navigation	2.1	-0.4	0.7	0.4

	Assumed value			
	10-'20	20-'30	30-'40	40-'50
Elasticity of the chemical industry	0.7	0.7	0.7	0.7
Fuel substitution for inland navigation fuel (%)	1.0	1.0	1.0	1.0

Note: [a] Compound annual growth rate (CAGR). Based on Vita et al. (2016), EUROSTAT (2017a) and EUROSTAT (2017b).

Production projection by categories

With the correlations defined, production equations were formulated for the projection by complex, geographical region (North Western Europe, Mediterranean Europe, Central Europe), and country.

Relative production of naphtha (2015=100) by a country of a complex in a geographical region in a year in comparison to the previous year was calculated as (Kim 2017):

$$P_{Naphtha,n,g,c,y} = P_{Naphtha,n,g,c,y-1} * \left(1 + \varepsilon_{chem} * \Delta GVA_{Chem,n,g,c,y}\right) \tag{1}$$

With:

-P (2015=100) as the relative production.

-ε as the elasticity.

-ΔGVA (%) as the annual GVA change.

-Indices: n as the complex, g as the geographical category, c as the country, y as the year and Chem as the chemical industry.

Using the linear correlations between the main drivers and the relative production of each refinery product, the equations (gasoline, jet fuel, diesel, heavy fuel oil, LPG, bunker fuel) were also formed. The relative production of bitumen, sulfur and coke were related to the initial production of gasoline, calculated as:

$$P_{q,n,g,c,y} = P_{q,n,g,c,y} * k_{q,n} \tag{2}$$

With:

-k as the base year production ratio between the initial production of gasoline and the product (bitumen, sulfur and coke)

-index: q as the specific product (bitumen, sulfur and coke)

By summing up all the relative production of each product, the production of a complex in a region by country was estimated as:

$$P_{t,n,g,c,y} = \sum P_{n,g,c,y} \tag{3}$$

With:

-index: t as the total, n as the complex, g as the geographical category, c as the country and y as the year.

Based on these equations, the production of each complex is projected using the base year production information by category and the main driver by country.

Reference scenario

Using the production projection inputs, the reference scenario was developed under the assumption that the refineries operate as they did without further effort to save energy or reduce CO_2 emission. The energy demand and CO_2 emission by each site in the base year were projected until 2050 linearly proportional to the production projection changes. Energy consumption (toe) of a refinery in a country for a year was calculated as (Kim 2017),

$$E_{r,c,y} = E_{r,c,B} * P_{t,n,g,c,y} \tag{4}$$

With:

-E (toe) as the energy consumption

-P (2015=100) as the relative production

-Indices: r as the refinery, c as the country and y as the year, B as the base year, t as the total, n as the complex, g as the geographical category.

The relative production, $P_{R,n,c,y}$ (2015=100), was calculated by summing up all the production of the products for each refinery characterized by given categories. Likewise, CO_2 emission (t) was calculated as (Kim 2017):

$$e_{r,c,y} = e_{r,c,B} * P_{t,n,g,c,y} \qquad (5)$$

With:
-e (t) as the CO_2 emission

Policy scenario

The Policy scenario was developed considering political inputs adopted from EU Roadmap by European Commission (2011).

To investigate the maximum achievable range of model responses based on activity assumption, the scenario, 'the decarbonization scenario under effective technologies and global action', was chosen as it was the most current ambitious GHG emission reduction path (80 % possible reduction by 2050 in comparison to the emission level in 1990). The main driver values were modified according to the inputs by each sector and applied to the production of the refineries and the consequent development of energy demand and CO_2 emission were analyzed.

First, in the transportation sector, there assumed more alternative fuel penetration in both road transportation and aviation activity. The fuel mix in the road transportation could change in 2050 from oil (87 %) and biofuels (13 %) in the reference scenario to oil (40 %), biofuels (28 %) and electricity (32 %) in the policy scenario (European Commission 2011).In the policy scenario, the alternative fuel penetration difference (54 % of more biofuels and electricity) was taken into account assuming the linear replacement from 2015 to 2050 (1.46 % annual average change).The fuel mix in aviation changes in 2050 from jet fuel (100 %) in the reference scenario, to jet fuel (58 %) and biofuel (42 %) in the policy scenario (European Commission 2011). The difference of 42 % of biofuel replacement of the jet fuel was included in the policy scenario with linear penetration assumption from 2030 to 2050 (2.1 % annual average change).

Second, for the industry sector, an increasing effort to reduce the energy intensity (energy demand per value added) was assumed. According to European Commission (2011), the energy intensity of the industry sector could reduce by 32 %, 53%, and 62% in 2005, 2030 and 2050 respectively. (compared to 1990) in the reference scenario. On the other hand, the energy intensity was reduced by 75 % in 2050 in the policy scenario. This further reduction in energy intensity (13 %) was taken as an input for the chemical industry sector in the policy scenario in this study assuming linear enhancement from 2015 to 2050 (0.37 % further annual decrease of energy intensity: In total 2.14 % decrease annually).

Finally, for the residential sector, for which the oil share was anticipated to decline to around 15 % by 2050 from around 25 % in 2010 in the reference scenario, the oil may practically be replaced by energy sources such as solar energy and biomass. As an input to the policy scenario, 0.375 % further decline (0.625 % of annual decrease in total) of the oil percentage in the residential fuel mix was modelled in the policy scenario.

2.3. Energy saving options (ESO)

ESOs are applicable to refineries to improve the energy efficiency of the processes by increasing productivity and/or decreasing energy intensity per process by using wasted heat or improve the technical designs (Worrell, Galitsky 2004). A selection of ESOs was investigated to be introduced into the model, based on technology descriptions in various literatures (Morrow III et al. 2013; Chan et al. 2015; Worrell, Galitsky 2004). The selection was conducted by criteria of a low current penetration rate and high energy saving potential. From the technology assessment based on Morrow III et al. (2013), five ESOs were chosen:

1. Installation of new internals for processes
2. Improvement of catalysts to reduce H_2 consumption
3. Flare gas recovery system
4. Revamp heat integration
5. Furnace air pre-heat

Morrow III et al. (2013) suggested fuel and electricity saving potential for the five selected ESOs by process in a generic refinery in the U.S. Based upon the study, percentage of potential fuel and electricity savings from the total energy demand by refinery were estimated. Table 2-9 shows the summary of estimated energy saving potential of the ESOs. The ESOs could be employed for multiple processes, leading to higher saving potentials for entire refineries than implied by the pure addition of the values presented in Table 2-7. For example, the saving option ‘installation of new internals’ may be applied to the CDU as well as the DSU process, increasing the refinery-wide potential. The ESOs were characterized economically by their payback periods from various literature sources. Table 2-10 shows payback periods of each ESO and the sources for these assumptions.

Table 2-9. Fuel and electricity savings of energy saving options in total refinery.

Number	Name	Fuel saving[a]	Electricity saving[b]
1	Installation of new internals	0-1.57 %	0.00-1.00 %
2	Flare gas recovery	1.09 %	0.67 %
3	Improvement of catalysts	0.20-1.17 %	0.01-0.13 %
4	Revamp heat integration	0.00-0.05 %	0.00-0.59 %
5	Installation of furnace air pre-heat	0.09-0.10 %	0.00 %

Note. [a] % from the total refinery fuel consumption, [b] % from the total refinery electricity consumption. Estimation based on Morrow III et al. (2013).

Table 2-10. The payback periods of the ESOs assumed in the study for the base year.

Energy saving options	Payback period (y)	Reference
1	0.7	(Darius Remesat 2010)
2	2.0	(Worrell, Galitsky 2004)
3	1.0	(Lapinski et al. 2012)
4	2.0	(Worrell, Galitsky 2004)
5	3.0	(Shekarchian et al. 2013)

Potential of energy saving options

To investigate the energy saving and CO_2 mitigation potential, diffusion paths of the energy saving options were included in the model. Figure 2-5 shows the process of how energy saving, and CO_2 mitigation potential were estimated.

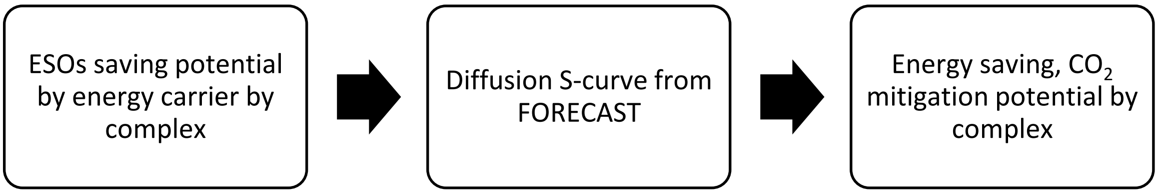

Figure 2-5. Methodology of identifying potential of energy saving options (Kim 2017).

First, the energy saving potential by ESOs were assigned to the applicable categories.
Second, the diffusion curves were created based on FORECAST modelling developed by Fraunhofer ISI. The model generated three diffusion curves: maximum diffusion, economic diffusion and minimum diffusion.
Maximum diffusion (or technical diffusion) shows how a technology may be employed assuming no economic limitations. The maximum diffusion could be restricted by technical conditions (e.g. competing use of resources like waste heat or other mutual exclusive paths to improve process efficiency). For the ESOs chosen in this study, the maximum diffusion value by 2050 was assumed to be 100 %, though, as no .

Minimum diffusion exhibits how the technology could be employed without apparent economic advantages that warrant upgrades of existing installations. The reasons for the adoption of the ESOs in this diffusion path may be due to environmental regulations, company-specific efficiency targets or regular stock turnover. Due to the increasing environmental regulation on flare gas in the future according to Comodi et al. (2016), the minimum diffusion of the flare gas recovery system was assumed to be 90 % whereas other technologies were assumed to be autonomously employed by 25 % in 2050.

Economic diffusion suggests the adoption path of the technology with economic conditions taken into account. Based on the FORECAST modelling, it was calculated based on payback periods. The longer the payback time is, the fewer of the refineries would employ the specific ESO and vice versa. This assumption was founded on expert knowledge at Fraunhofer ISI, asserting that the payback period is commonly used as a as major decision criterion in industry when investments of relatively minor economic relevance have to be made. Figure 2-6 shows the relationship between the diffusion parameters and payback periods used in this study, adopted from FORECAST modelling by Fraunhofer ISI.

As the payback period increases, the diffusion parameter, which indicates the adoption percentage of technologies in the economic diffusion from the maximum diffusion case (100% in this study), decreases. After a certain point, in this case assumed to be around 12 years, the technologies are no longer adopted by industries. Based on this diffusion method, the economic diffusion lies in between the maximum diffusion and the minimum diffusion (see Figure 2-7 for the example of diffusion curves for saving option 1 used in this study). Using these specific parameters for the economic diffusion, we can observe that the maximum diffusion is never reached. This implicitly models stock turnover and hesitant investors and can, in principle, be used to simulate a decrease in available capital due to less favorable business environments for refineries (e.g. in the policy scenario). However, in order to increase the compatibility of the scenarios presented here, this variation is not included.

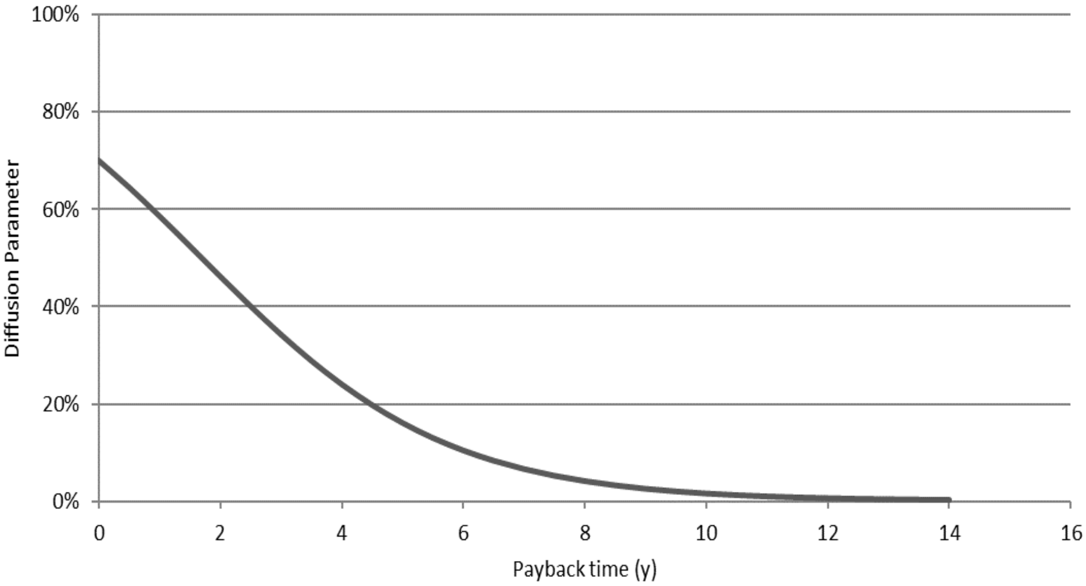

Figure 2-6. Diffusion parameter with respect to payback periods in FORECAST modelling (Kim 2017).

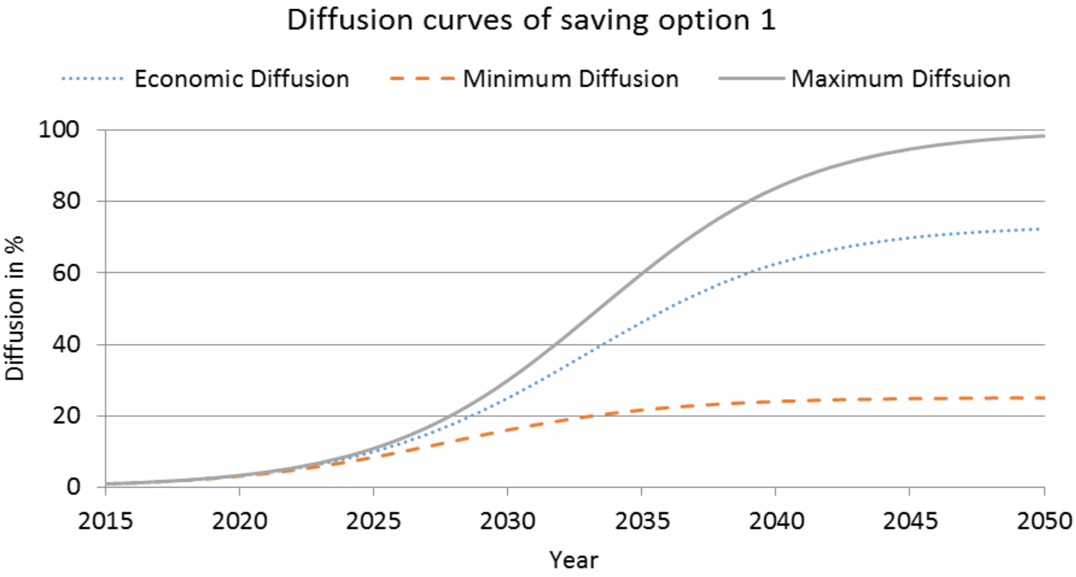

Figure 2-7. Example diffusion S-curves generated from FORECAST modelling (Kim 2017).

The final process for the potential estimation was to apply ESOs on applicable refineries by their categorization. Using the diffusion curve of each ESO and their saving potential data, energy saving and CO_2 mitigation potential values by each complex was calculated until 2050.

3. Results

The summary of the main result of the study is shown in Figure 3-1. First, the capacity of the refineries, energy demand, and CO_2 emissions were analyzed according to the categorization. Second, the site-level calculation of energy demand and CO_2 emission are displayed. Third, the CO_2 emission change in the scenario analysis is shown. Lastly, the energy saving potential and CO_2 reduction potential are included.

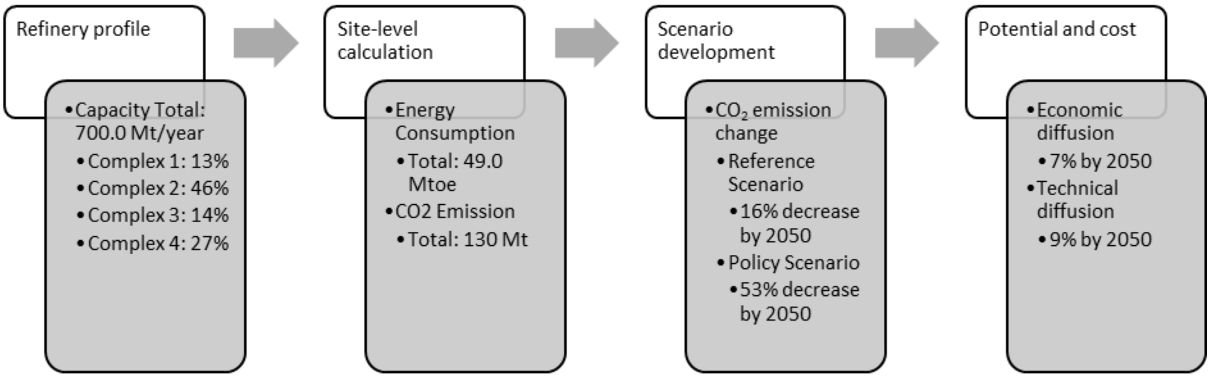

Figure 3-1. Main result summary of the study along with the research process (Kim 2017).

3.1. EU-28 Status Quo by Complex

The 98 refineries in EU-28 had a total CDU capacity of about 700.0 Mt/year (Oil and Gas Journal 2016). An analysis using the categorization showed that Complex 1 without any conversion unit had the smallest capacity (13 %). Complex 2 with a FCCU unit had the biggest capacity (47 %) and Complex 4 with both FCCU and HCU showed 25 % of the capacity and lastly Complex 3 with a HCU unit had 15 %.

The site-level calculation of total energy demand and CO_2 emission by the refineries in EU-28 were shown to be about 49.0 Mtoe and 130 Mt CO_2 respectively.

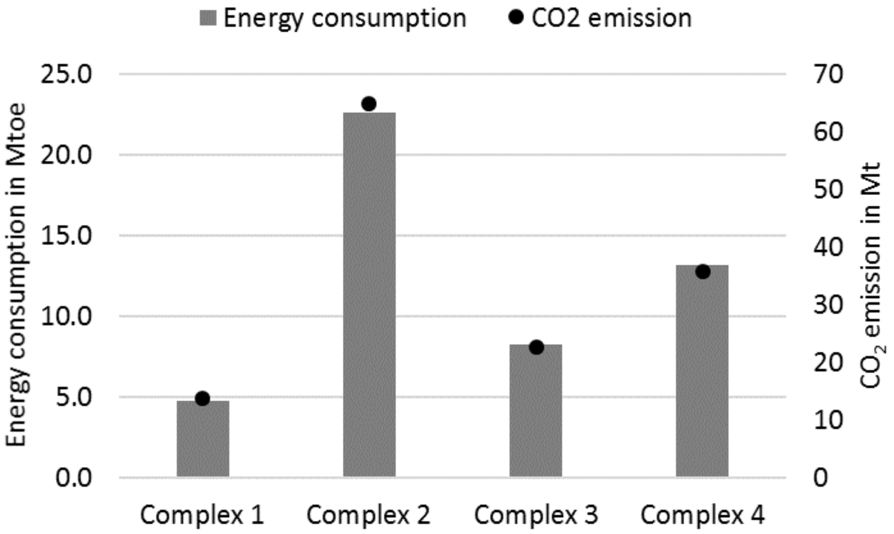

Figure 3-2. Total energy demand and CO_2 emission by complex (Kim 2017).

The percentage of the contribution by each category showed the same order with similar magnitude as capacities (Figure 3-2). Complex 1 had about 5.0 Mtoe of energy demand and released about 18 Mt CO_2, which were about 15 % from the total energy demand and the emission. Complex 2, which showed the highest capacity contribution, used about 23.0 Mtoe and released around 65 Mt CO_2, which were estimated to be about 46 % and 47 % from the total energy and emissions respectively. Complex 3 consumed about 8.0 Mtoe of energy and emitted about 23 Mt CO_2 approximately, which were about 17 % from the total. Complex 4 spent about 13.0 Mtoe and released around 36 Mt CO_2, which were about 27 % and 26 % in the total energy and emissions, respectively.

3.2. The Reference and Policy scenario

Production projection by complex

In the reference scenario, the production levels in all complexes decreased (Figure 3-3). The decrease in the period between 2015 and 2030 was expected to be larger than in between 2030 and 2050. Particularly, the decrease rate by Complex 2-4 slowed down significantly from 2030 until 2050. Overall, the projection showed 15-20 % reduction of the production until 2050.

By complex, due to the significant reduction in oil demand in the residential sector assumed already in the reference scenario, Complex 1, which relied on the heating and power sector the most, indicated the biggest reduction of the production by about 15 %, 18 % and 20 % until 2030, 2040 and 2050, respectively. Complex 2, Complex 3 and Complex 4 showed heavy dependency on the transportation sector (around 70 %). Driven by the decline of gasoline and diesel demand, the production decreased at a lower rate than residential sector, it therefore showed a smaller decrease than Complex 1. The production of Complex2-4 were projected to reduce by around 12 % until 2030, around 13 % until 2040 and about 15 % in 2050. The decreases showed significantly slower rates from 2030 to 2050, following the main driver pathways. Among Complex 2-4, Complex 4 was less dependent on the transportation and more on the industry sector (i.e., Naphtha: chemical industry), due to their distinct product slates. Hence, the projection of its production suggested the lowest decrease. Complex 2 produced more gasoline than diesel. Therefore, due to the higher reduction in gasoline demand than diesel demand in the reference scenario, its production reduced slightly lower than Complex 3.

All these activity changes were soley driven by the assumptions about the main drivers (and to a minor extent, their elasticity) and were therefore, heavily dependent on the selected scenario. This becomes even more clear when looking at the policy scenario (Figure 3-4)

In comparison to the projections in the reference scenario, a higher reduction in the production levels of all complexes was observed.

Particularly, the projection of all complex suggested significant decreases from 2040 to 2050 due to the complete transition of the fuel structure in the residential sector to non-oil products.

The production of Complex 1, affected by the residential fuel mix change the most, showed a drastic decrease of about 70 % until 2050. The projections of Complex 2-4 suggested the reduction by around 60 % due to the further electrification of the transportation sector by 2050 compared to the levels in 2015. Overall, around 70% of the market for oil products (space heating and mobility) existing in 2015 is more or less decarbonized in 2050, leaving only the chemical industry as reliable customer in this scenario.

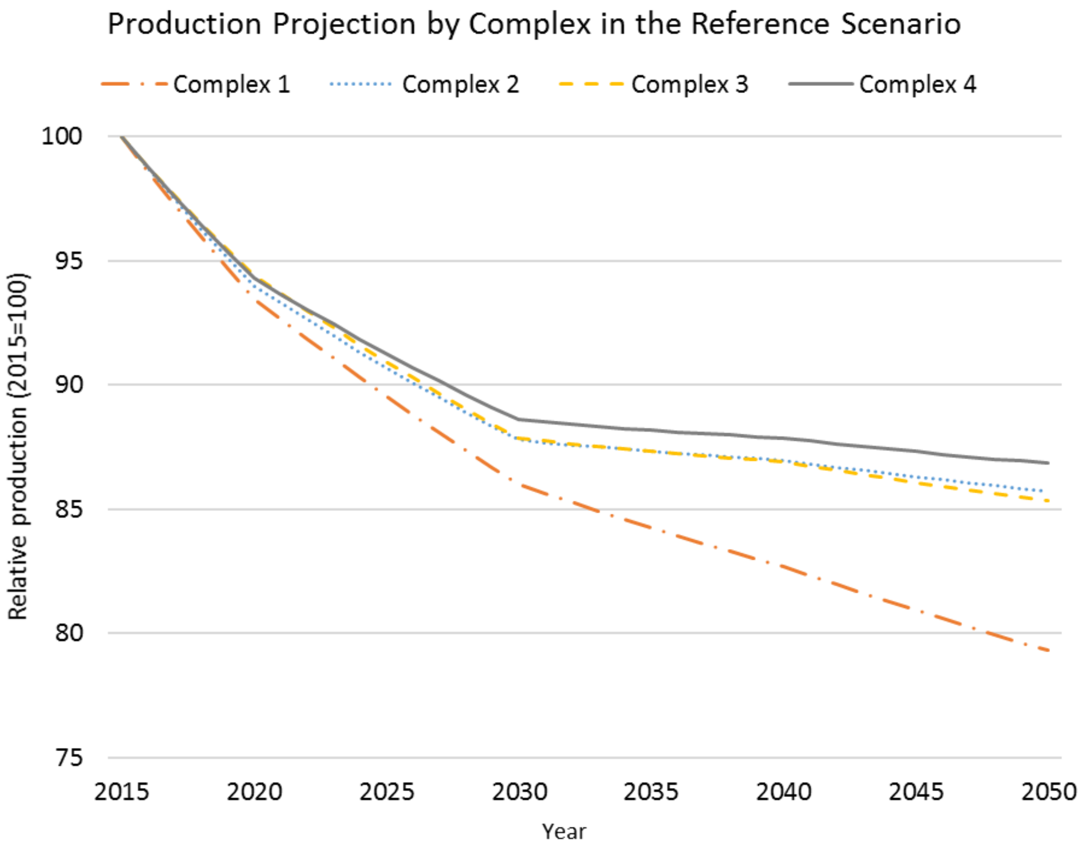

Figure 3-3.Production projection by complexes in the reference scenario (Kim 2017).

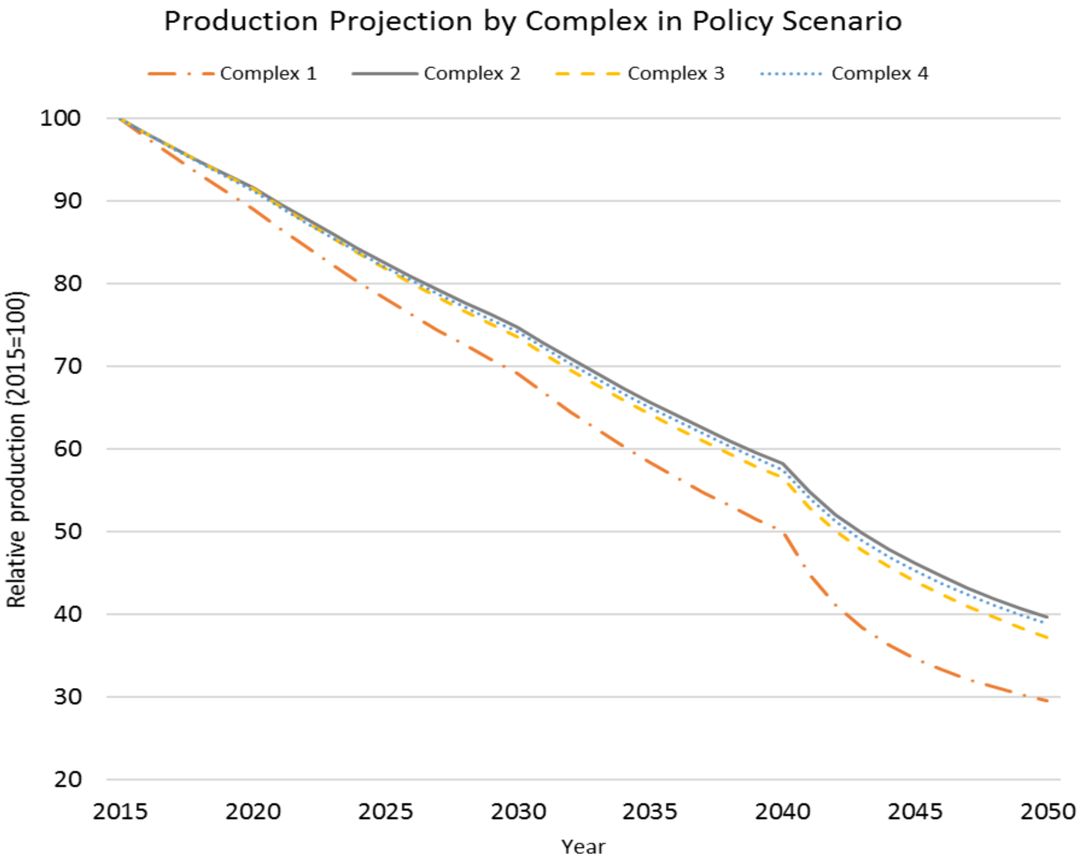

Figure 3-4. Production projection by complex in the policy scenario (Kim 2017).

Energy consumption and CO_2 emission projection

Based on the production projections, CO_2 emission (see Figure 3-5) and energy demand projections in both reference and policy scenario without applying the energy saving options were developed. In the reference scenario, the energy demand and CO_2 emission level (49.0 Mtoe, 130 Mt CO_2) in 2015 were suggested to decline to around 42.0 Mtoe and 119 Mt CO_2 (-13 % compared to 2015) by 2030 and to around 41 Mtoe and 115.0 Mt CO_2 (-16 % compared to 2015) by 2050. These reductions appeared to be bigger in the policy scenario in both energy demand and CO_2 emission projections, which seemed to show the reduction to around 36.0 Mtoe and 101.0 Mt CO_2 (-26 % compared to 2015) to around 19.0 Mtoe and 54 Mt CO_2 (-61 % compared to 2015) further by 2050. Especially, the projections in the policy scenario proposed significant reductions from 2040-2050 driven by the complete fuel transition in the residential sector.

In comparison to the reference scenario, both energy demand and CO_2 emission were suggested to decline more in the policy scenario by around 13 % by 2030 and by about 44 % by 2050 (see Figure 3-5).

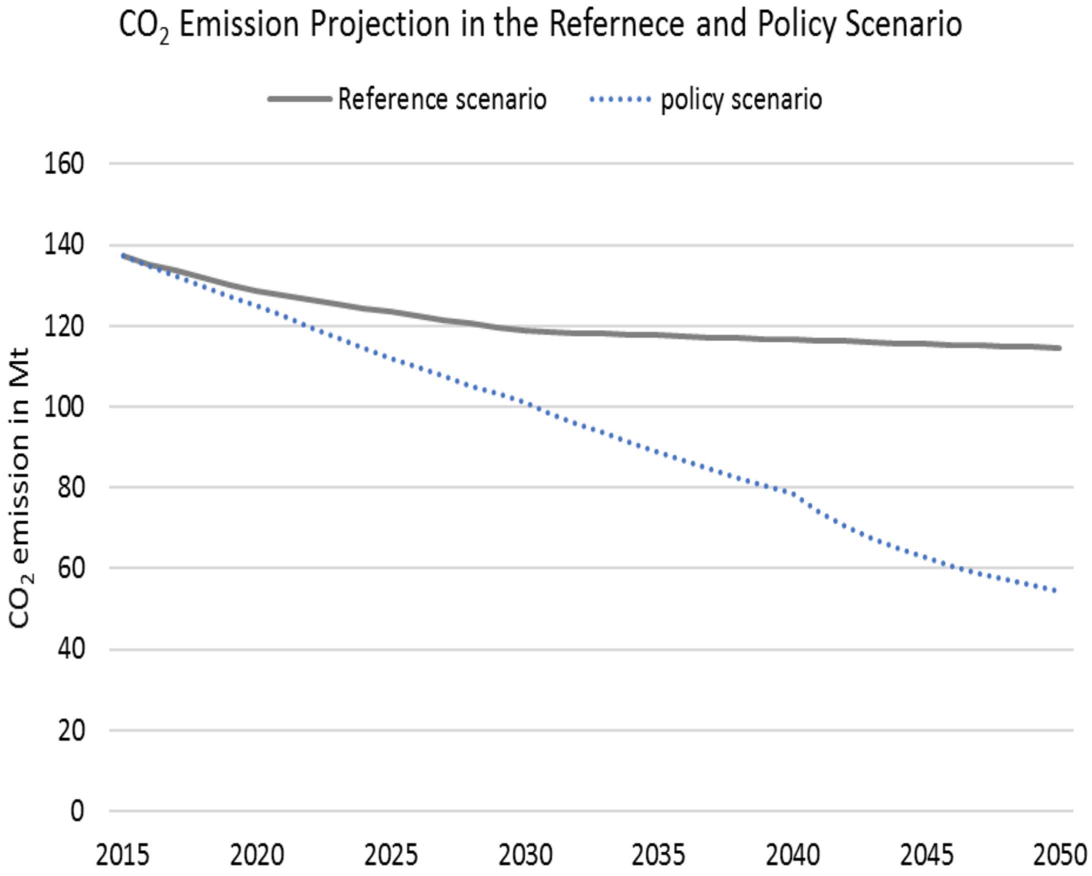

Figure 3-5. CO_2 emission projection in the reference and policy scenario.

3.3. Potential of Energy Saving and CO_2 Mitigation

The ESOs were applied to the reference and policy scenario projections under technical and economic diffusion conditions to identify the energy saving and CO_2 mitigation potential. In total, six lines were depicted in both energy demand projection and CO_2 emission projections: Reference scenario-without ESO, reference scenario-technical diffusion case, reference scenario-economic diffusion case, policy scenario-without ESO, policy scenario-technical diffusion case, policy scenario-economic diffusion case. Figure 3-6 exhibits developed projections of CO_2 emission in both technical and economic diffusion of the ESOs compared to both the reference and the policy scenario without the ESOs applied. The results suggested that in the technical and economic diffusion cases, 2-3 % of energy savings (0.9-1.3 Mtoe) and CO_2 mitigation (3-4 Mt CO_2) potential could be achieved in comparison to the reference and policy scenario without the application of the ESOs in

2030. Furthermore, the projections proposed about 7-9 % of energy savings (2.7-3.8 Mtoe) and CO_2 mitigation (8-11 Mt CO_2) potential in 2050 in the technical and economic scenario in comparison to the reference and policy scenario without applying the ESOs. As mentioned before, the values given for the policy scenario do not take into account that energy efficiency investments in refineries may become unlikely if their business model wavers.

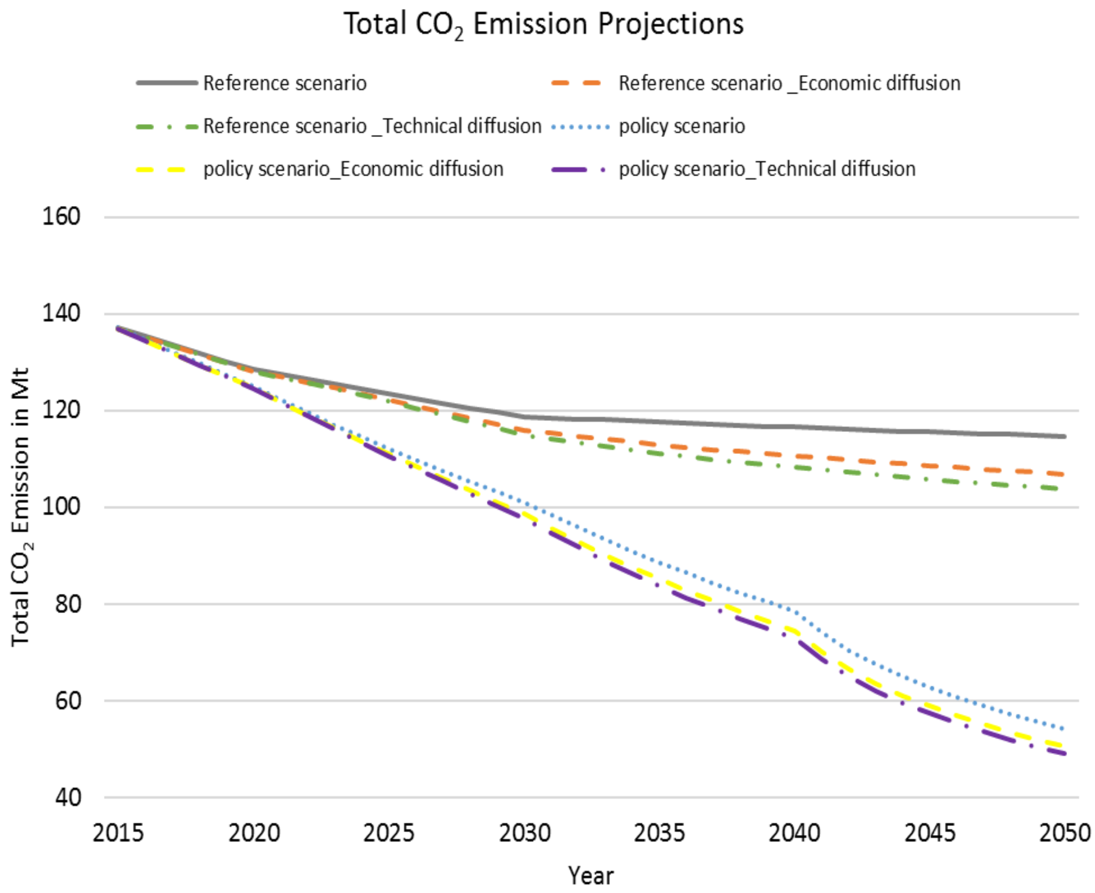

Figure 3-6.CO_2 emission projections in the different scenarios and diffusions (Kim 2017).

4. Discussion

4.1. Refinery Status-Quo

The analysis of the status-quo of the refineries showed that Complex 2 had the highest contribution to energy demand and CO_2 emission, which implies the EU-28 refineries are geared towards gasoline production (though, compared to other markets, the diesel share is rather high). Compared to Reinaud (2005), an increase of the capacity contribution could be observed for Complex 3 (by around 4 %) and Complex 4 (by around 1 %) whereas Complex 2 showed the reduction by about 7 % from 2005 to 2015. This change of the capacity ratio is in line with the trend of increasing diesel demand and decreasing gasoline demand in Europe (Calzado Catalá et al. 2013). It suggests that an effort may have been made by the refinery sector to respond to the demand change of the oil products. Additionally, since HCUs have a higher energy intensity than FCCUs, the trend of configuration ratio changes towards producing more diesel could cause higher energy intensity and consequently higher CO_2 intensity in the refinery sector.

The model shows site-level calculation which could be used as a basis for the bottom-up approach with great potential for accuracy. However, to calculate the energy demand of the refineries more accurately, the model should be further improved by including site-specific efficiency in process level, utilization of each process and the fuel supply structure by site, as data on this becomes available. Moreover, crude sources and, regulation on quality of the refinery products could have impact on the product slate, energy consumption and CO_2 emission. To further improve the model, these exogenous factors could be considered.

4.2. Scenario Development

In both reference and policy scenario analysis, production projection by the categories proposed that the production of Complex 1 decreased the most, driven by its dependency on the residential sector. The higher reduction in Complex 2-3 production compared to Complex 4 is caused by the scenario assumption that the oil product demand in the transportation sector decreases more than in the industry sector. Overall, the refineries in EU-28 are likely to show lower utilization rates, which could lead to change of product slates, and structural changes (e.g., use it as terminal, shut-down).

In the reference scenario, both energy demand and CO_2 emission were observed to decrease by about 13 % by 2030 and by around 16 % by 2050. Based on the study by Chan et al. (2015), both production and energy demand in the refinery sector in Europe were suggested to decrease by around 12-14 % by 2050, which does not differ significantly from the result of our study.

In the policy scenario, around 70 % of the emission was mitigated in 2050 when compared to the 2015 level. The EU road map in European Commission (2011) showed a 88 % decrease of the GHG emission in the energy intensive sector in the policy scenario. The difference between the literature and our study could be explained by inputs from the report that were not considered in this paper such as employment of carbon capture and storage system and further efficiency improvement in the transportation and residential sectors.

Compared to the reference scenario, energy demand and CO_2 emission suggested a decline further by 53 % in 2050 in policy scenario. The comparison between the reference scenario and the policy scenario suggests that, in order to reach the target of EU, 80-95 % of CO_2 reduction by 2050 in comparison to 1990, political inputs on the demand side of refineries could play an important role. Furthermore, the difference between the reference scenario and the policy scenario could imply the significant production reduction in the refinery sector in the policy scenario, which could lead to their change of operation, product slate changes and fundamental structural changes.

The scenarios analysis shows significance in showing different production changes by refinery category and how it could lead to energy demand and CO_2 emission change. The analysis, however, has its limitations from the assumption that the product demand and refinery production in the EU are linearly correlated. The model does not take into account international trading, for example, which could affect the production of the EU refineries based on their competitiveness. Second, the model does not include competition between products produced among different complexes. The products from different category of refineries could have various qualities (e.g., octane number for gasoline) or expense, which could result in different impact of the main drivers. Third, the model does not include the rigidity of the refineries' production. For instance, in reaction to the market demand, Complex 1 is not able to produce lesser heating oil and more kerosene since its production is confined to its crude oil source. This could impact the competitiveness of the refinery types considerably.

To further improve the model, exogenous factors such as international trading could be included. Furthermore, competition between each complex, its production rigidity could be factored into to increase the validity of the model. All of these potential improvements depend on increased data availability.

4.3. Potential of Energy Saving Options

Potential analysis of energy saving options (ESOs) in both reference scenario and policy scenario showed energy saving and CO_2 mitigation potential of about 7 % and 10 % in economic and technical diffusion scenarios by 2050 respectively. Comparably, Chan et al. (2015) suggested technical potential of 23 % and economic potential of 9 % by 2050 in comparison to the reference scenarios in EU refinery sector. Furthermore, Worrell, Galitsky (2004) found out technical potential energy savings of 20-30 % that were technically feasible and around 10-15 % with economic factors considered. The difference in potential estimation could be explained by the technologies considered since in this paper, we restricted the analysis to five technologies that were not yet applied, assumedly with highest potential, whereas in the mentioned studies, all the technically viable options were all taken into account. Generating economic diffusion trend by using payback period is a common approach as a criterion in the industry sector. However, the model does not reflect on the disinvestment possibility when refinery production declines, causing lower capital availability and more hesitant opinions regarding long-term investments. For the improvement of the model, production and profit structure of the refineries could be taken into account for the decision of adopting ESOs.

5. Conclusion

In this paper, the status quo of the refineries in EU-28 was studied on site-level. The result showed that European refineries relied on Complex 2, which has a FCCU for the optimal production of gasoline, the most. Furthermore, production changes by refinery category until 2050 were projected by assigning the correlations between main drivers and each refinery product in the reference and policy scenario. The production projections in both scenario suggested that the production of the refineries would decrease, where Complex 1 suggested the biggest decline implying Complex 1's upcoming challenges in the future oil product market. The energy demand and CO_2 emission projections proposed the reduction by around 16 % by 2050 in comparison to the level in 2015 in the reference scenario and around 53 % of further reduction by 2050 in the policy scenario, suggesting the effect of the political inputs to comply with the EU's GHG reduction target of 80-95 % by 2050 in comparison to 1990 level. Furthermore, the refinery sector, in both scenarios, could face a significant production decrease, which might lead to changes of the operation conditions, changes of product slates, and structural changes in the refinery sector.

Finally, five energy saving options (ESOs) were considered to show the potential energy saving and GHG mitigation under technical and economic conditions using a S-curve diffusion used in the energy demand simulation model FORECAST developed by Fraunhofer ISI. The results showed around potential energy saving and CO_2 mitigation of 7-9 % in the diffusion cases by 2050 compared to the scenarios without applying the ESOs.

The paper uses a detailed projection methodology assuming correlations between refinery products and main drivers from several sectors (transportation, industry, heating). Furthermore, it is characterized by use of different refinery categories differentiated by its process configuration with product slates. However, the methodology leaves out factors such as international trading, the economic structure of refineries, competitions between refineries and rigidity of their production by category.

For the future work, it could be interesting to elaborate more of site-specific data such as utilization rates by process, and ratios of electricity and steam purchased by the refineries. For the scenario analysis, it would be interesting to include the trading system of international refinery product markets that could affect the production by EU refinery sector. Furthermore, to identify more comprehensive mitigation potential, more ESOs can be included as well as other mitigation options such as carbon capture and storage systems. On top of that, the decision factor for mitigation option adoption would be interesting to be considered into the model when the production level decreases.

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