Concawe
Environmental Science
for European Refining

Review

Volume 27 • Number 1
July 2018

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Editor: Robin Nelson, Concawe

Foreword

As the July 2018 edition of the Concawe *Review* is about to be published, the news and weather channels are reporting the record high temperatures of summer 2018, providing further evidence of climate change. Following COP 21, Concawe initiated several new programmes touching on areas where the refining industry can contribute both in the short term as well as the longer term transition to a carbon-neutral future. In this *Review* we include four articles emanating from this work.

The first article looks at the latest improvements in the technology to control emissions of unwanted pollutants from diesel engines, vital to maintain diesel engines in the car manufacturer's arsenal to reduce CO_2 emissions in cars. This is followed by an article on the climate impact of reducing SO_2 from international shipping and the complication that SO_2 in the lower atmosphere can contribute as a climate coolant.

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The third article in this *Review* is on the development of a methodology for a life-cycle analysis allowing an assessment of the full impact of different drivetrain options and thereby improving the understanding of the overall CO_2 emissions from electric as well as internal combustion engine passenger vehicles.

The fourth technical article summarises the work of the ReCAP project to evaluate the potential for, and the cost of, deploying carbon capture and storage (CCS) in European refineries.

My thanks to the authors for these valuable insights into some of the challenges we face as we work to mitigate climate change. I also would like to thank Dr Mike Spence for his contribution to the work of Concawe as Science Executive for both the Water, Soil and Waste and the Oil Pipelines management groups.

Contents

A comparison of the impacts of Euro 6 diesel passenger cars and zero-emission vehicles on urban air quality compliance

A Concawe study aims to determine how real-driving emissions from the latest Euro 6 diesel passenger cars will impact ambient air quality compliance under different scenarios, and compares the results with a scenario where all new passenger cars are replaced with zero-emission vehicles.

Introduction

Emission reduction measures have resulted in significant improvements in overall air quality in Europe. However, air quality continues to be a challenge in many urban areas, and non-compliance with air quality limit values (AQLVs) remains an issue, especially for nitrogen dioxide (NO_2) and particulate matter (PM).

In many cities, road transport has been the primary focus for emission reduction measures, and diesel passenger cars in particular are often assumed to be one of the main causes of non-compliance with AQLVs. However, technology to reduce emissions from diesel vehicles has made significant advances in recent years. To ensure that measured reductions in vehicle emissions more accurately reflect improvements in real-world driving emissions, a new real-driving emissions (RDE) test procedure that measures vehicle emissions under more realistic real-world conditions, and therefore provides more accurate information on the emissions generated in urban environments, has been introduced. [1]

Concawe commissioned two studies in 2017 to determine the expected emissions from the latest Euro 6 diesel passenger cars (including Euro 6d vehicles certified since September 2017) under the new testing methodology, and to understand how the emissions from Euro 6 diesel cars would impact ambient air quality compliance when compared with zero-emission vehicles (ZEVs). The first study, completed by Ricardo,[2] focused on determining the actual and expected real-driving emissions for multiple classes of Euro 6 vehicles (Euro 6b, Euro 6c, Euro 6d temp, Euro 6d). The study evaluated data obtained from literature as well as from Ricardo's own tests on a number of diesel passenger cars run using the newly developed on-road RDE test procedure and other real-world driving cycles. A prediction of how different Euro 6 vehicles, including the most advanced (Euro 6d) vehicles, would perform was provided. The study concluded, from existing data, that real-world NO_x emissions from diesel passenger cars are significantly reduced by successive improvements in Euro 6 legislation. It further concluded that when technical solutions currently being introduced are applied to Euro 6d cars, these vehicles are expected to meet the EU NO_x emission standard for Euro 6 passenger cars of 80 mg/km under RDE test conditions.

A second Concawe study carried out with Aeris Europe incorporated the data from the Ricardo study and used a state-of-the-art model to explore the impact of diesel passenger cars on NO_2 and PM compliance, and on population exposure under different scenarios, including a scenario where all new passenger cars are replaced with zero-emission vehicles. This study is an extension to the Concawe Urban Air Quality Study[3] which explored how urban air quality is affected by the emissions from vehicles and domestic combustion. The 2017 Aeris study extends the original study to focus on urban air quality in every major town and city in the EU that has an air quality monitoring station. It covers nearly 2,500 European air quality monitoring stations and includes a detailed analysis of air quality compliance and population exposure within 10 selected European cities. The approach and the key findings of this study are highlighted in this article. Additional detailed information can be found in Concawe Report 8/18.[4]

Modelling approach—compliance scenarios

The Aeris study used AQUIReS+, a suite of modelling tools developed in house by Aeris, to investigate the impact that fleet turnover to the latest Euro 6 diesel passenger cars would have on NO_2 and PM compliance during the period 2020–2030 throughout the EU-28. A detailed analysis was also performed for the following 10 European cities: Antwerp, Berlin, Bratislava, Brussels, London, Madrid, Munich, Paris, Vienna and Warsaw.

A Base Case emissions scenario was used as a starting point for all diesel passenger car scenarios in the modelling. This Base Case scenario is based on the January 2015 TSAP16 WPE (Working Party on Environment of the European Council) Current Legislation Baseline Scenario,[5,6] associated with the EU Air Policy Review process[7] as generated by the IIASA GAINS model.

The results of the Ricardo study were used to derive conformity factors[1] which were used to generate the different emission scenarios for AQUIReS+. Among the multiple emissions scenarios examined, the following two were used as key scenarios to illustrate the predicted results for NO_x:

- Ricardo Median Scenario: All Euro 6 diesel passenger cars introduced in a specific year are assumed to conform to the median level of the Ricardo results. This scenario assumes that all new diesel passenger car registrations from 2020 onwards are Euro 6d.
- ZEV Scenario: All new diesel passenger car registrations from 2020 onwards are replaced by zero tailpipe-emissions vehicles undertaking the same number of kilometres driven.

Details of the two scenarios are given in the following tables:

Table 1: Ricardo Median Scenario

SCENARIO	DESCRIPTION	YEARS	CF
Ricardo Median Scenario	Euro 6b pre-2015	Pre-2015	5.41
	Euro 6b post-2015	2015–2016	1.90
	Euro 6c	2017–2019	1.21
	Euro 6d temp	2020+	1

Table 2: ZEV Scenario

SCENARIO	DESCRIPTION	YEARS	CF
ZEV Scenario	Euro 6b pre-2015	Pre-2015	5.41
	Euro 6b post-2015	2015–2016	1.90
	Euro 6c	2017–2019	1.21
	Zero-exhaust vehicles	2020+	0

[1] A conformity factor (CF) is a simple coefficient of the legislated limit value (LLV) of 80 mg/km. For example, a conformity factor of 1.5 is one and a half times the LLV. This was introduced in Commission Regulation (EU) 2016/427 of 10 March 2016.

These scenarios have been chosen for detailed analysis, as they illustrate the effect that the largest reduction in emissions would have compared with an average emissions scenario. Additional results from all the scenarios examined can be found in Concawe Report 8/18.[4]

For particulate matter, two emission scenarios were considered. The first used the Base Case emissions and the second modelled the elimination of all diesel exhaust emissions for new passenger cars registered from 2020. PM emissions associated with tyre and brake wear and road abrasion remained unchanged between the scenarios.

Nitrogen oxide emissions

Figure 1 shows the Base Case NO_x emissions in Germany from all diesel passenger cars, broken down by Euro standard. Every country in the study possesses a unique vehicle fleet composition and subsequent emissions profile, each of which shows a similar evolution of emissions. Germany has been chosen as a representative example to illustrate these trends.

Figure 1: Diesel passenger car NO_x emissions in Germany—Base Case

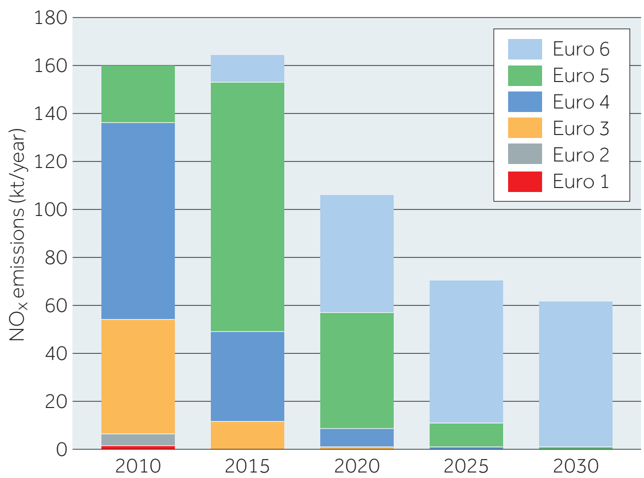


Figure 2 on page 7 shows the diesel passenger car NO_x emissions in Germany for the Ricardo Median Scenario. A reduction in Euro 6 diesel passenger car emissions from 2015 onwards is shown, with a nearly two-thirds reduction by 2030 as a result of improved emissions from diesel car technologies. The diesel passenger car NO_x emissions in Germany for the ZEV Scenario are shown in Figure 3.

Figure 2: NO_x emissions from diesel passenger cars in Germany—Ricardo Median Scenario

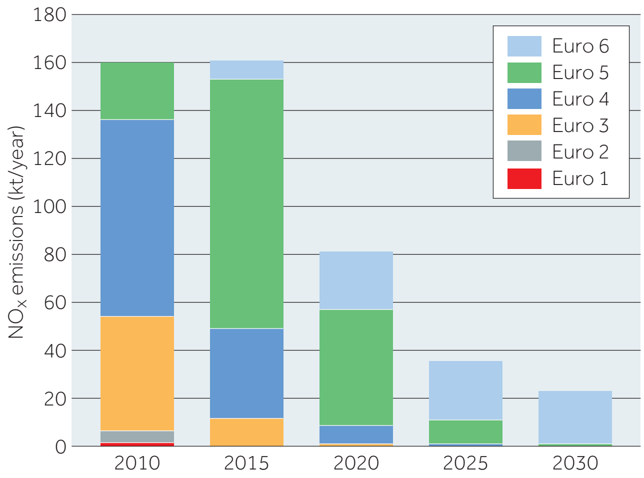
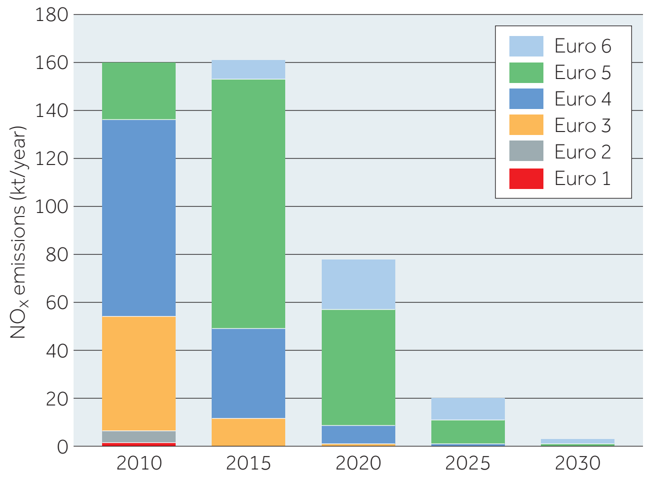


Figure 3: NO_x emissions from diesel passenger cars in Germany—ZEV Scenario



Particulate matter emissions

Figure 4 shows the Base Case emissions of $PM_{2.5}$ from all diesel passenger cars broken down by Euro standard over time in Germany, while Figure 5 shows the $PM_{2.5}$ emissions based on the ZEV Scenario. Successful implementation of exhaust treatment systems removes nearly all PM exhaust emissions. The remainder of the PM emissions are abrasive emissions from road, brake and tyre wear. As the non-exhaust component is produced independently of the vehicle powertrain, a switch to zero-emission vehicles will not affect this aspect and may actually increase this number as a function of increased vehicle mass.[8] In this study, no attempt was made to modify emissions in the ZEV Scenario to take into account vehicle mass.

Figure 4: Primary $PM_{2.5}$ emissions from diesel passenger cars in Germany—Base Case

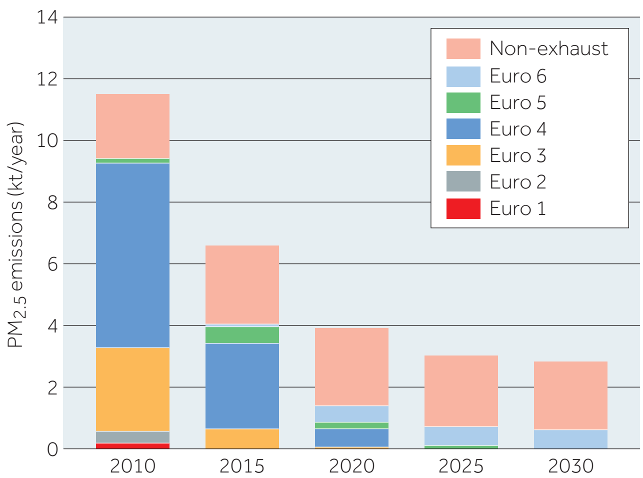
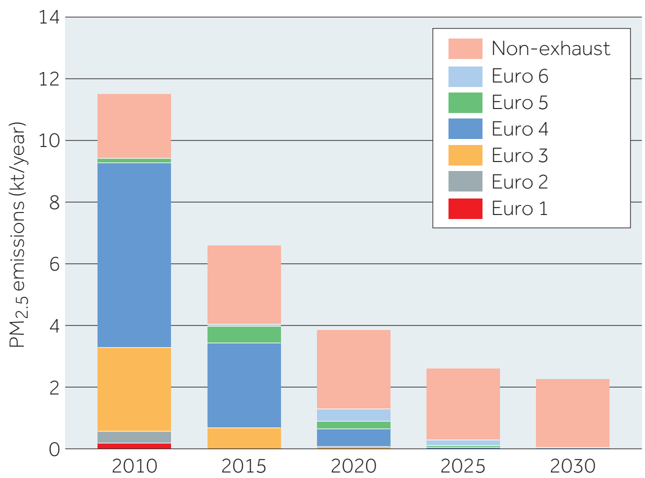


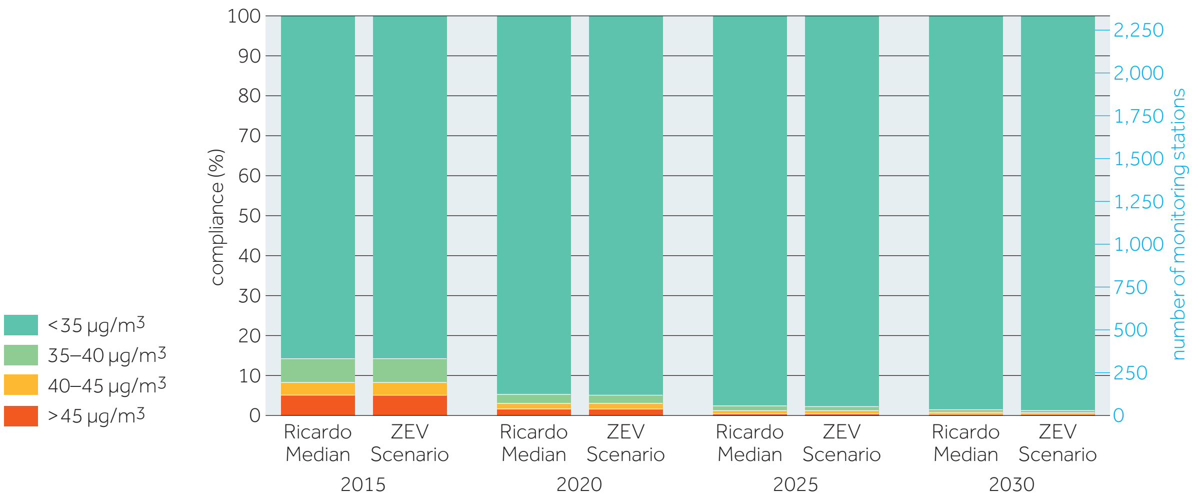
Figure 5: Primary $PM_{2.5}$ emissions from diesel passenger cars in Germany—ZEV Scenario



Results — nitrogen dioxide

Figure 6 shows the modelled compliance of NO_2 monitoring stations across the EU-28 for the Ricardo Median and ZEV Scenarios. The results show that, by 2020, roughly 2% of stations are predicted to be non-compliant, with a further 1.5% predicted to be possibly non-compliant. This is observed in both the Ricardo Median and the ZEV Scenarios which both exhibit a similar evolution of compliance over time. The difference in the overall number of stations achieving compliance between the two scenarios is just above 0% in 2020, less than 0.1% in 2025 and 0.2% in 2030. This strongly suggests that the progressive replacement of older diesel passenger cars by Euro 6d diesel cars will show a similar improvement in urban air quality compliance compared to a replacement with zero-emission vehicles.

Figure 6: NO_2 station compliance across the EU-28 for the Ricardo Median and ZEV Scenarios

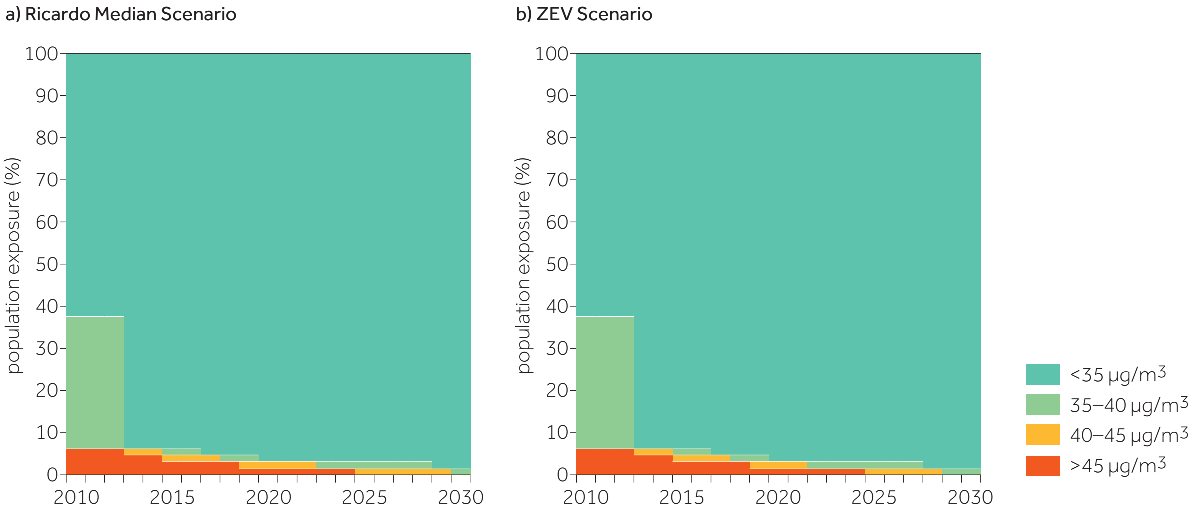


In terms of population exposure, the Aeris modelling[2] at city level shows that there is almost no difference between the Ricardo Median and ZEV Scenarios. Figure 7 on page 9 shows the exposure of the population of Munich[3] according to the two scenarios. No difference is seen between the two scenarios until 2022 and even then, the only difference is the shift of a single year forward in the ZEV Scenario. Ultimately both scenarios result in the same level of population exposure in 2025 and 2030. The same overall conclusion is true of other cities evaluated.

[2] The model uses the population exposure methodology described in the EEA paper, *Exceedance of air quality limit values in urban areas*.[9]

[3] Munich was chosen as a representative city; relevant findings were predicted for other cities.

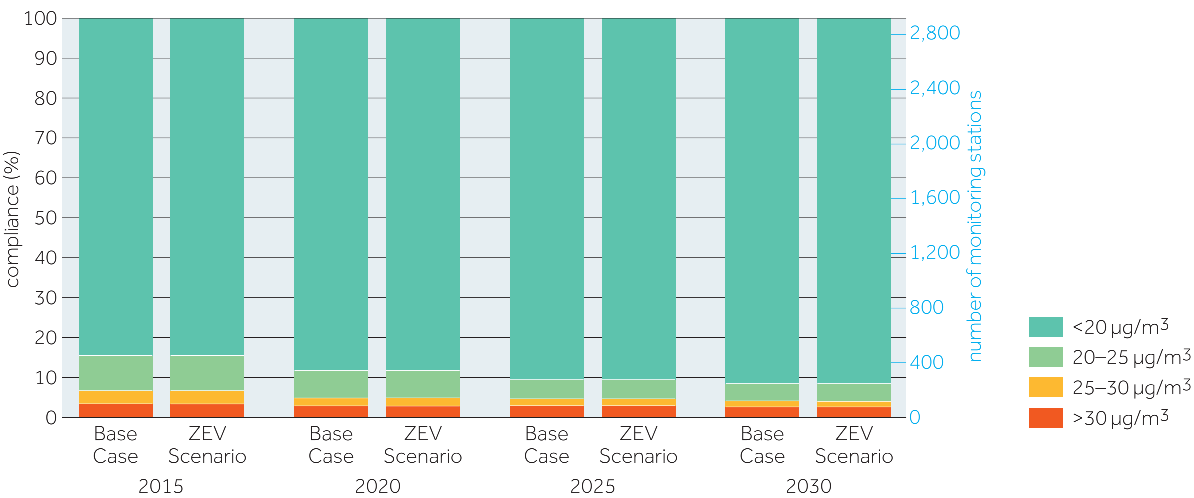
Figure 7: Population exposure to NO_2 in Munich—Ricardo Median and ZEV Scenarios



Results—particulate matter

Given the similar particulate emissions from Euro 6 diesel passenger cars and zero-emission vehicles it is not expected that there will be any change in air quality in terms of PM compliance. This is confirmed in Figure 8 which shows the modelled compliance of $PM_{2.5}$ monitoring stations across the EU-28 for the Base Case and the ZEV Scenario. The results show that by 2020 roughly 3% of stations are predicted to be non-compliant with a further 2% predicted to be possibly non-compliant. This is observed in both the Base Case and ZEV Scenarios which exhibit a similar evolution of compliance over time. This strongly suggests that non-compliance across the EU-28 is unrelated to Euro 6d diesel passenger cars, given that their substitution with zero-emission equivalents has no effect on overall compliance.

Figure 8: $PM_{2.5}$ station compliance across the EU-28 for the Base Case and the ZEV Scenarios



Conclusion

The results of the study indicate that the latest Euro 6 technologies will deliver a significant reduction in emissions of nitrogen oxides compared to pre-2015 vehicles. Euro 6d is expected to achieve the 80 mg/km limit or better, under real-world driving conditions. Additionally, in the turnover of the vehicle fleet from older vehicles to new vehicles, the latest Euro 6d diesel vehicles will be as effective as zero-emission vehicles in helping cities become compliant with air quality standards. The modelling shows that almost no difference in population exposure is expected between the Ricardo Median and ZEV Scenarios.

In the case of particulates, given that diesel particulate filters have been effective in managing PM, emissions from modern passenger cars are largely independent of the drivetrain, with mechanical abrasion (brake, road and tyre wear) being the most significant source. This means that both electric and newer diesel passenger cars produce essentially equivalent emissions for a given vehicle weight and driving habit. Therefore, in any areas experiencing $PM_{2.5}$ or PM_{10} non-compliance, the level of improvement will be similar for both new ICEs and EVs.

Further developments in new vehicle emission standards or measures that exclude new diesel cars from cities are unlikely to deliver earlier compliance or a reduction in population exposure. An analysis of local sources of pollutants is needed to effectively address the remaining non-compliant areas and to identify the most effective mitigation measures.

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Climate impacts of particulate pollutants emitted from international shipping

International shipping represents a large sector for heavy fuel oil consumption. Ocean-going ships are estimated to contribute up to 2–3% of long-lived greenhouse gas emissions annually.[1] In addition, these ships simultaneously emit a considerable amount of other pollutants including particulate matter (PM) and precursors such as sulphur dioxide (SO_2). These small airborne particles converted from ships' exhausts could directly reflect ('direct aerosol effect'), or cause clouds to reflect ('indirect aerosol effect'), more sunshine back to space, cooling down the planet and partly counteracting global warming from greenhouse gases.[2] Furthermore, ocean-going ships travel across open oceans that are difficult for aerosols from land-based emission sources to reach due to their short lifetimes (1–2 weeks). As a result, aerosols emitted from ships might have a climate impact that is more than proportional to their mass contribution. International shipping emissions (ISEs) contribute only about 5% (5.6 Tg S yr^{-1}) to total anthropogenic sulphur emissions.[3] However, their total climate forcing via cloud radiative effects (CREs) due to ships' exhausts perturbing marine stratiform clouds could be more than 10% in total anthropogenic aerosol forcing, according to a recent study conducted by Dr Chien Wang's group (sponsored by Concawe) at MIT.[4]

A Concawe study aims to provide a better understanding of the uncertainties relating to the climate impacts of international shipping emissions.

In the study, the researchers have applied a state-of-the-science Earth system model, the Community Earth System Model (CESM), developed by the National Center for Atmospheric Research (NCAR) and the U.S. Department of Energy (DOE). To address the detailed aerosol-climate interaction, the group has also utilised an advanced aerosol module developed in-house—the two-Moment, Multi-Modal, Mixing-state resolving Aerosol model for Research of Climate, or MARC.[5,6,7] MARC uses seven lognormal modes to represent the size distributions of sulphate and carbonaceous aerosol population: three modes for sulphate with different sizes, one of each for pure black carbon (BC) and pure organic carbon (OC), one of each for mixtures of BC-sulphate (core-shell structured; MBS) and OC-sulphate (internal mixture; MOS). MARC predicts total particle mass and number concentrations within each of the seven modes based on the assumption of the lognormal distribution of particle size. In addition, carbonaceous mass concentrations inside MBS and MOS are also predicted. Therefore, the mass ratios of the mixed aerosols evolve over time, changing the optical and chemical properties of the mixed aerosols. Mineral dust and sea salt are each represented by four bins with fixed sizes in MARC. Their emissions are calculated by the land and atmospheric component model of CESM, respectively. MARC connects to the cloud physics module of CESM through a new aerosol activation scheme developed by the group. Compared with similar previous studies, the CESM-MARC model has more physical-based and detailed representations of aerosol-cloud interactions, as well as direct aerosol effects. For the purpose of comparison, the group has also deployed CESM with the default aerosol module, MAM[8] in the study.

CESM-MARC or CESM-MAM were run at a horizontal resolution of 1.875°×2.5° and 30 vertical layers, and in two configurations:

1. Runs with ocean data, in which CESM-MARC or CESM-MAM were run with prescribed sea surface temperature, sea ice, and greenhouse gas concentrations, at their year 2000 levels; and
2. Fully-coupled runs, i.e. with fully-coupled atmosphere, ocean, sea ice and land components.

The former configuration is used to derive radiative effects of aerosols, while the latter is used to calculate long-term climate responses.

Physical processes involved

Among various aerosols emitted from ocean-going ships, the sulphate or sulphate-containing aerosols are efficient cloud condensation nuclei; they have a substantial influence on the formation of marine clouds and their micro- and macro-physical properties. On one hand, marine stratiform clouds have a strong cooling effect on the climate system. They cover about 30% of the global ocean surface, and can reflect more solar radiation back to space than the dark ocean surface under cloud free conditions.[9] On the other hand, low-altitude marine stratiform clouds form and develop near the ocean surface (at only a few degrees cooler than ocean surface) and thus have limited impacts on the long-wave radiation balance.[10] Therefore, the annual-mean net cloud radiative effect (CRE) at the top of the atmosphere (TOA), a measure of the cloud radiative effect in reference to clear sky conditions, is negative (i.e. cooling) and can be up to $-20\ W\ m^{-2}$ on the global scale.[2] Consequently, even a few percent change in marine stratiform clouds, either by aerosols or other factors, can either enhance or offset substantially the anthropogenic global warming due to greenhouse gases. It is therefore expected that the most effective impact of ship-emitted aerosols is to alter the properties of these low-altitude marine clouds that are otherwise often at a considerable distance from other anthropogenic emissions.

In addition to ship-emitted sulphur compounds, another significant component in the atmospheric sulphur cycle over oceans is the oceanic phytoplankton-derived dimethyl sulphide (DMS). DMS can be oxidized by hydroxyl radical (OH) or nitrate radical (NO_3) to produce SO_2 and eventually be converted to sulphate aerosols. Total global emissions of DMS are estimated to be about 18.2 Tg S yr^{-1} based on model simulations, and about one third of these are oxidized to sulphate aerosols (6.1 Tg S yr^{-1}), which is comparable to sulphates emitted from shipping.[11] Aerosols from this natural pathway play the same role in controlling cloud formation as those from shipping emissions.

Defining the radiative effects of ship-emitted aerosols

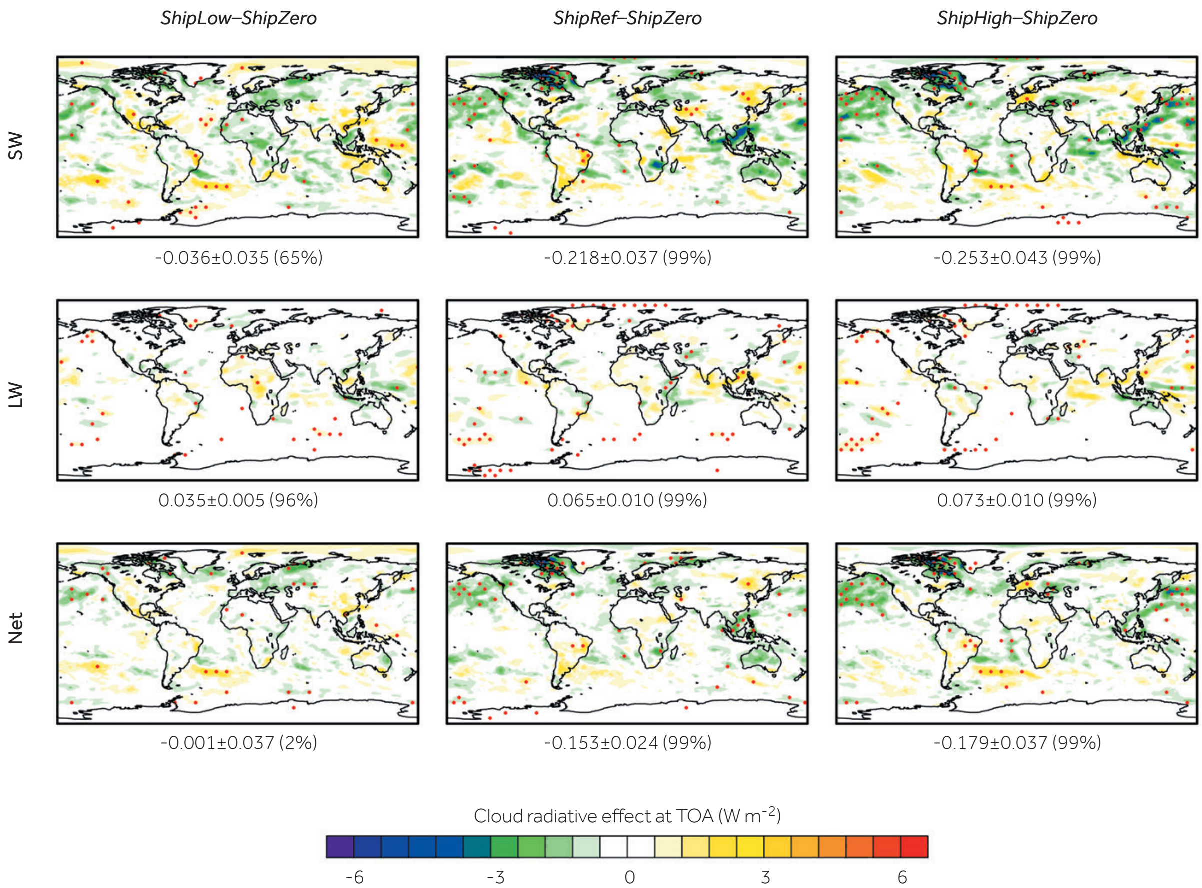
To facilitate an assessment of both direct (DRE or direct radiative effects) and indirect radiative effects (measured by perturbation or CRE by aerosols) of ship-emitted aerosols, the group has designed a comprehensive set of experiments. All simulations use the aerosol emissions in 2000, except for shipping and DMS emissions.

For shipping emissions, three scenarios were designed based on the assumption of sulphur content in the fuel oils used by ocean-going ships. Currently, the average sulphur content is 2.7%, which is equivalent to about 5.6 Tg S $year^{-1}$; this is referred to as *ShipRef*. On the other hand, as of 2013, the high-sulphur fuel oil that has 3.5% sulphur content (and which is still permitted outside the Emission Control Areas) is referred to as *ShipHigh*. However, the IMO has planned to lower the sulphur content to 0.5% outside the Emission Control Areas after 2020, and the corresponding scenario is referred to as *ShipLow*. In the *ShipLow* and *ShipHigh* scenarios, the total global sulphur shipping emissions are 1.0 and 7.2 Tg S $year^{-1}$, respectively. The differences between these three scenarios and a zero shipping-emission scenario, or *ShipZero,* represent how various regulations on ship fuel influence the shipping emission-induced CRE.

To consider the uncertainty of DMS emissions and thus different levels of natural aerosols particularly over remote oceans overlapping ship tracks, different annual emissions of DMS are designed as well, with a base scenario of 18.2 Tg S year^{-1} (*DMSRef*), and a low scenario with half of base emissions (*DMSLow*) as well as a scenario excluding DMS emissions (*DMSZero*).

Twelve simulations paring different emission scenarios of DMS and ship emissions have been conducted. Each simulation runs for 32 years driven by 12-month cyclonic climatological sea surface temperature, with the first 2 years as spin-up and discarded. The global mean direct radiative effect of ship-emitted aerosol is −23.5 mW m^{-2} and is derived by comparing *ShipRef_DMSRef* and *ShipZero_DMSRef*, with the strongest negative (cooling) DRE in the areas with intense shipping tracks, from mid-latitude Pacific Ocean and Atlantic Ocean, to South China Sea, North Indian Ocean and the Red Sea. The accumulation-mode sulphate contributes 89% to total global DRE, followed by the OC-sulphate mixture (MOS). The contributions of other aerosol species are very limited (note that BC and MBS provide net positive forcing). The magnitude of DRE is within the range from −50 to −10 mW m^{-2} of previous studies.[12,13]

Figure 1: Spatial patterns of simulated cloud radiative effects (CRE; units: W m^{-2}) of international shipping emissions at various shipping emission levels (*DMSRef*)



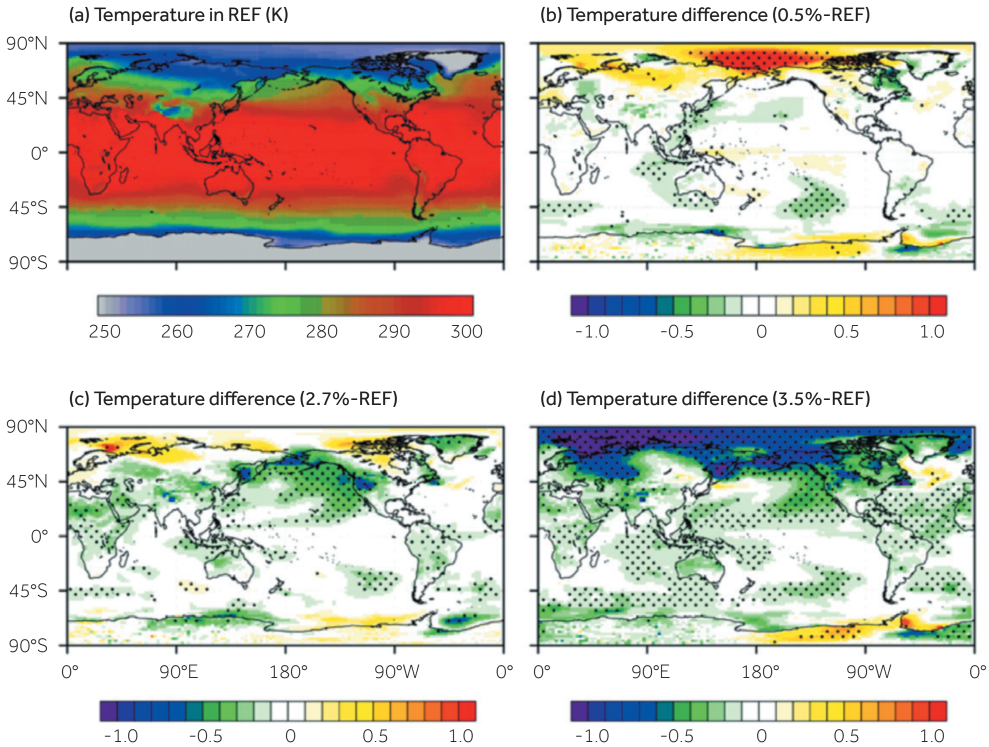
The CREs created by ship-emitted aerosols, however, are about an order of magnitude higher than the DREs and show different spatial patterns under various shipping emission regulations (Figure 1). The CRE is calculated as the differences of radiation flux at TOA and at all-sky conditions, between the simulation without shipping emissions and three simulations with various shipping emissions levels (i.e. low, reference, high) and keeping DMS emissions unchanged at the reference level. Predicted differences in short-wave (SW), long-wave (LW) and net (SW+LW) are shown in Figure 1, averaged over the 30-year simulation period. The numbers below each panel on Figure 1 are the global means, standard deviation across the 30-year period, and the confidence level. The red dots represent grid points that are statistically significant above the 90% confidence level based on the two-tailed Student's t-test.[4] At reference shipping emissions, significant cooling CRE in shortwave radiation (SW; calculated by *ShipRef_DMSRef - ShipZero_DMSZero*, the same for other quantities) is simulated in areas of mid-latitude Pacific Ocean and the Baffin Bay between Canada and Greenland, with a global average of -0.218 W m^{-2}. The long-wave (LW) CRE shows a global average of +0.065 W m^{-2}. Consequently, the global net CRE (SW+LW) is -0.153 W m^{-2} with a similar spatial pattern to that of SW. At the high shipping emissions (*ShipHigh_DMSRef*), the net CRE changes as expected to -0.179 W m^{-2}, and more areas show significant changes than in *ShipRef_DMSRef*. However, at the low reference level of shipping emissions (*ShipLow_DMSRef*), fewer areas demonstrate significant changes compared to *ShipRef_DMSRef* and *ShipHigh_DMSRef,* and the global averages of the CRE are not significant at a 90% confidence level at SW and net. These results indicate that more stringent shipping emission regulations proposed by the IMO to be applied after 2020 could effectively reduce or even largely eliminate the net CRE induced by shipping emissions.

Interestingly, researchers find that the shipping emission-induced CRE exhibits very different patterns and global averages at different emission levels of DMS. With DMS emissions ranging from the reference level to low and zero levels, the shipping-induced cooling CRE at SW increases from -0.218 to -0.457 and -2.435 W m^{-2} on the global scale, respectively. This is because the natural aerosol from DMS causes shipping emission-induced changes in cloud droplet number and water content, and thus radiative effects. Similarly, the shipping emissions could also influence the DMS emission-induced CRE and cloud properties. Generally, stronger cooling CRE (-8.492 vs -6.463 W m^{-2}) induced by DMS emissions are seen when shipping emissions are ignored, particularly in areas of intense shipping tracks, such as the North Indian Ocean, mid-latitude areas of the Pacific Ocean and the Atlantic. This finding reveals a critical interplay between anthropogenic and natural aerosols particularly over remote oceans.

Ongoing estimation of the net climate responses of ship-emitted aerosols

The group is currently analysing results from a set of long-term fully coupled model simulations. The preliminary result in the equilibrium simulation set indicates that using 2.7% and 3.5% sulphur content in fuel would cause a global average cooling of 0.2° or more (Figure 2). Besides scenarios with different levels of sulphur content in ships' fuel, black carbon aerosols emitted from international shipping will also be quantified. This type of simulation applies a constant forcing to an often 100–150 year long integration where oceans are allowed a long adjustment time to absorb extra heat. Another set of simulations are conducted to estimate the relative climate impacts on temperature in comparison with CO_2 with the 'global temperature potential' metric.

Figure 2: (a) Surface temperature in reference run; (b)–(d) Surface temperature change relative to reference run in simulation with ship fuel sulphur content at 0.5%, 2.7%, and 3.5%, respectively. All results are last 40-year means from a 150-year long integration.[4]



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Life-cycle analysis—a look into the key parameters affecting life-cycle CO_2 emissions of passenger cars

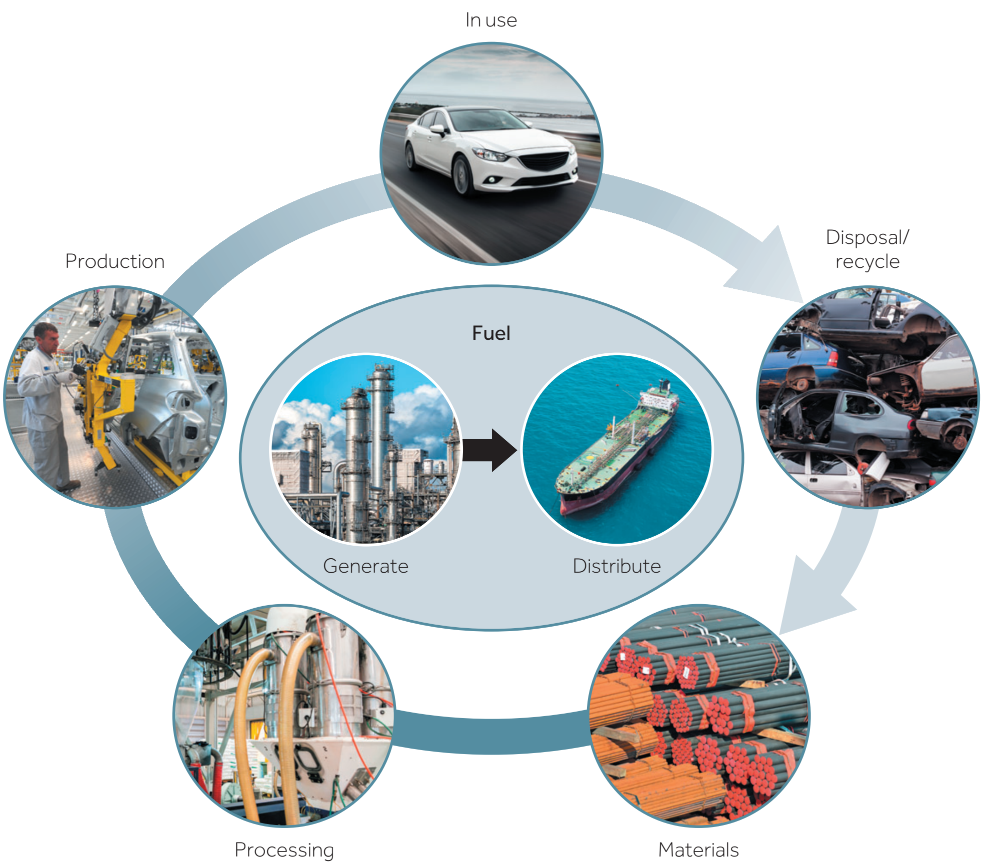
Introduction

This article presents the basis of a Concawe analysis comparing the life-cycle CO_2 emissions of battery-electric vehicles (BEVs) and internal combustion engine (ICE) vehicles, and investigates the impact of a range of key parameters on total CO_2 emissions.

The general framework and guidelines for a life-cycle assessment (LCA) are defined in ISO 14044:2006. This standard defines the general principles of a methodology used to assess the environmental impact of different products, from the extraction of the raw materials, through their use and finally recycling or disposal of the end-of-life and waste materials. Figure 1 shows how an LCA would apply to vehicles.

When applied to the CO_2 emissions associated with a vehicle, the LCA includes the well-to-wheels (WTW) emissions generated in the production and consumption of different fuels, as well as the CO_2 emissions associated with the production and disposal of the vehicle, including the batteries in the case of electric powertrains.

Figure 1: LCA applied to vehicles—a bigger picture



The aforementioned ISO 14044:2006 standard, despite providing general guidelines, is not specific enough to ensure a single and homogeneous methodology for conducting an LCA for fuels and powertrains. As an example, different methodologies to assess the energy consumption associated with battery manufacture can be found in recent literature, leading to very different results. Beyond the different approaches used, there is also a need to access more detailed and public data from manufacturers to ensure the robustness and representativeness of the final results. While these limitations prevent the LCA methodology from being used more widely, it is commonly agreed that such an analysis provides the key elements to perform a full technical comparison of the environmental impact of distinct energy/propulsion alternatives such as internal combustion engine (ICE) vehicles and battery electric vehicles (BEVs).

Concawe has used the LCA methodology to assess the CO_2 emissions associated with different fuel and powertrain combinations. This article presents the basis of that analysis, and investigates the impact that certain key parameters may have across the whole life cycle of a vehicle. The results and figures included are initial estimates based on relevant external publications and on Concawe's own internal research. Concawe is willing to engage with external stakeholders to assist in defining a standard LCA methodology to be applied to fuels and powertrains in the future.

Using LCA to assess CO_2 emissions from passenger cars

Basis

When comparing different electric vehicles with conventional powertrains, and the relative impacts associated with the energy or fuel generation, materials extraction, and manufacturing and production phases, the contributions to the total life-cycle emissions are distinct. The key parameters affecting the results are summarised in Table 1.

Table 1: Key parameters affecting vehicle LCA

	INTERNAL COMBUSTION ENGINE (ICE)	BATTERY ELECTRIC VEHICLE (BEV)
Non-road factors * * The % of non-use emissions of different powertrains may vary from 20–30% for ICEs, and from 30–70% for BEVs depending on the key parameters identified.[1]	● Vehicle class (e.g. A, B, C) ● Drivetrain materials (steel, aluminium) ● Production of the fuel	● Vehicle class (e.g. A, B, C) ● Drivetrain materials (copper) ● Battery production • Type (materials) • Size / Range • Cell production country • Battery assembly area • CO_2 estimation model ● Energy use for electrical generation (well-to-tank) ● Carbon intensity of the electricity mix
Road factors	● Vehicle use • Lifetime (years) • Total kilometres driven • Use (urban, rural, etc.) ● Type of fuel (e.g. petrol/diesel) ● Fuel consumption • Quantity (l/100 km) • Drive cycle (NEDC, WLTP, RDE)	● Vehicle use • Lifetime (years) • Total kilometres driven • Use (urban, rural, etc.) ● Unit consumption • Quantity (kWh/100 km) • Drive cycle

Table 2: Concawe LCA simple modelling tool—main inputs

PARAMETER	VALUE	COMMENT	SOURCE
Driving distance	150,000 km	To ensure that no battery replacement is required.	Concawe estimate.
Embedded emissions (battery manufacturing)	150 kg CO_2/kWh	Lithium ion battery (NMC). Top-to-bottom approach. Default value assumed constant regardless of the battery size (simplification). Energy use for battery manufacturing: 350–650 MJ/ KWh.	Average value from IVL report.
Embedded emissions, vehicle manufacturing	4 t CO_2/vehicle (Class B) 5 t CO_2/vehicle (Class C) 7 t CO_2/vehicle (Class D)	Generic values (lack of data per individual vehicle).	Based on NTNU.
EU electricity mix (low voltage, including losses)	350 g CO_2/kWh low voltage (2016). Preliminary estimate (see comments and sources).	2016 EU LV electricity mix (EU-28) **preliminary estimate** based on adjusted IEA data (WEO 2017 + JRC/JEC methodology including upstream emissions and losses). Reference: 2013: 447 g CO_2/kWh (JRC detailed analysis). 2016: 300 g CO_2/kWh (IEA WEO) EU electricity generation mix (HV without upstream emissions).	2016: Concawe preliminary estimate (subject to change once the updated JRC work is public).* 2013 value: JRC detailed analysis.[2] IEA WEO 2017.
Electricity/fuel consumption	Variable	Specific for each model considered.	OEM brochures.
Real-driving emissions (RDE) adjustment factor	1.4	Correction factor used to uplift fuel consumption from NEDC (New European Driving Cycle) to RDE values.	Concawe estimate. Conservative value aligned with other sources (EU Commission modelling).
Charging losses	10%	Default value aligned with 90% on-board battery charger efficiency (Conservative value. Fast charging not included).	Based on NTNU, Ricardo data.
End-of-life (EOL) emissions	0.5 t CO_2/vehicle (BEVs) 0.4 t CO_2/vehicle (ICEs)	Battery ≈ 20% of total EOL emissions for BEVs.	Based on NTNU data.

* JRC is currently working on a paper calculating the 2015 LV CO_2 intensity value using the most recent IEA statistic data issued with 2 years of delay (detailed methodology).[2]

The influence of some of these parameters have been explored by Concawe, and the initial results are presented below based on information currently available in external sources such as NTNU,[3] IVL,[4] European Commission data adapted from BMVI[5] as well as different OEMs' brochures for individual vehicles. Based on these sources, Concawe has developed an LCA model to explore different country-specific scenarios and run a sensitivity analysis on the key parameters across all vehicle segments. This model is intended to be a live tool to conduct periodic assessments as new data become publicly available. The main inputs used are summarised in Table 2 on page 19.

Sensitivity analysis

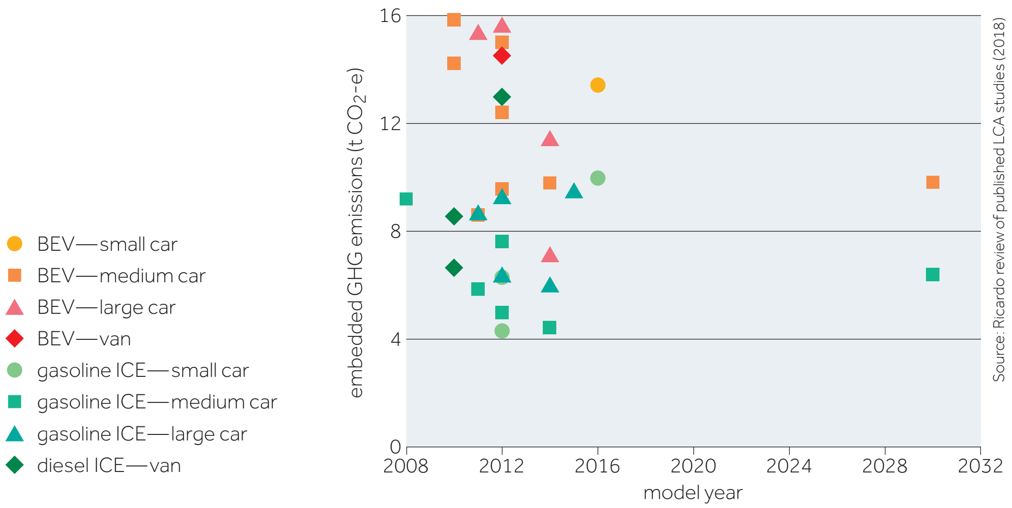
Manufacturing stage: battery type and size, and electricity mix used

Different published LCA studies show a wide variability in the embedded CO_2 emissions of BEVs related to the battery manufacturing process. Generally, these show that BEVs have higher embedded greenhouse gas (GHG) emissions than equivalent gasoline and diesel ICEs primarily due to:

- **Methodological factors** such as the chosen life-cycle inventory (LCI) database or the LCA methodology used (top-down or bottom-up approach). The selection of the manufacturing calculation method is one of the main causes of the discrepancies in embedded emissions found in literature. While top-down studies allocate energy use based on information about the individual process, the bottom-up approach aggregates data from each individual activity including energy consumption from utilities and additional auxiliary processes. The top-down approach causes higher greenhouse gas emissions and cumulative energy demand.
- **Battery pack** size and chemistry/technology used; this also determines the energy density of the package.
- CO_2 intensity of the **energy mix used** during the manufacturing and assembly process, usually performed in different locations.

Figure 2 shows the results of an LCA comparison recently conducted by Ricardo.

Figure 2: Summary of embedded GHG emissions for light-duty vehicles



In terms of the BEV emissions, the LCA impact of the battery is mainly caused by the production chains of three components: the battery cells, the cathode and the anode, comprising together approximately 55% to 85% of the battery's total impact.[6] Table 3 summarises the contribution of different elements to the final embedded CO_2 emissions associated with the battery manufacturing (and recycling) process.

Table 3: Summary of the embedded CO_2 emissions in the battery manufacturing (and recycling) process

	kg CO_2-e/ kWh battery			
Component	**Raw material and refining** [a]	**Battery grade material production (including mining and refining)** [b]	**Manufacturing (component and cell + battery assembly)**	**Recycling**
Anode	2–11	7–25		
Cathode	7–18	13–20 (90[c])		
Electrolyte	4	4–13		
Separator	<0.5	Approx. 1		
Cell case	<0.1	Approx. 1		
Battery case	4–13	10–25		
Cooling	0–3	2–6		
Battery management system (est.)	<1	4–30		
TOTAL	18–50	48–121 (216)	20–110	Pyro: 15 Hydro: -12
Most likely value *(based on the assessment of transparency and scientific method done in the report)*		60–70	70–110	15

[a] Example based on material needed for a 253-kg battery. (Ref. Ellingsen *et al.* (2014),[6] and data from Table 14 of the IVL report[4] where the varied results from using different cradle to gate datasets for material extraction and production are illustrated.)

[b] Ranges based on a review of battery LCAs. (Ref. Table 15 in the IVL report.[4])

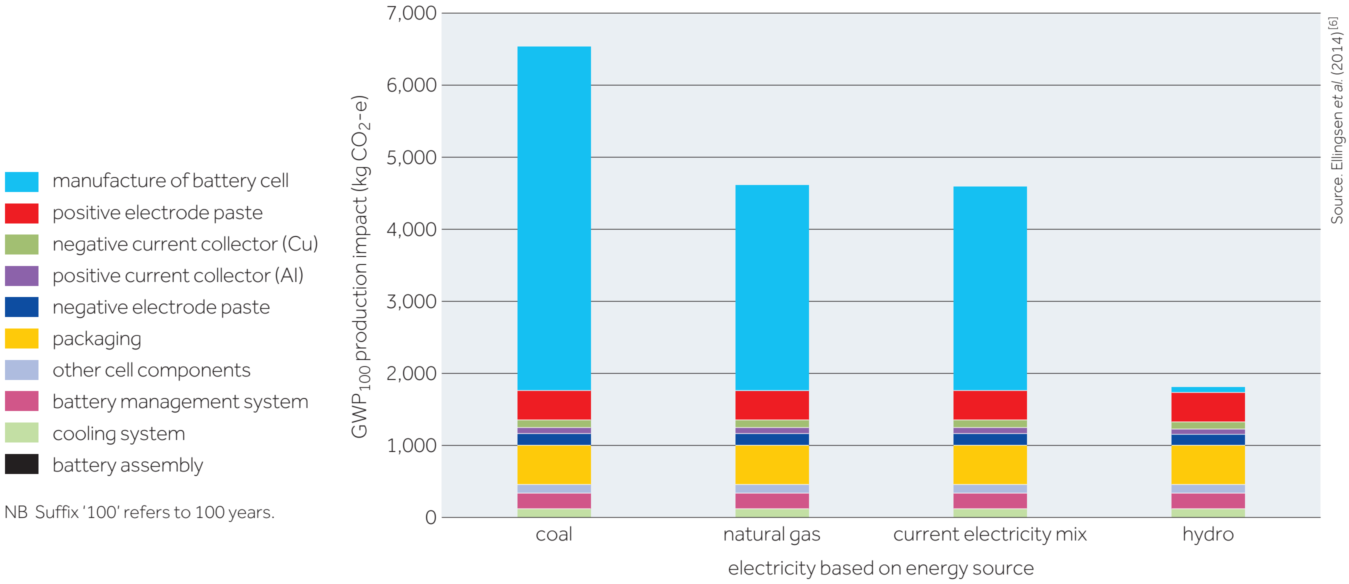
[c] Values in brackets are based on a report with approximate assumptions regarding processing materials.[7]

Source: IVL (2017)[4]

The electricity mix used during the manufacturing process of the different battery components has a significant impact and, as illustrated in Figure 3 on page 22, notable differences can be observed depending on the location (country) where both the manufacturing and assembly processes take place. As extreme cases, and as extreme references for individual countries, NTNU estimates that the potential impact of moving from a coal-based electricity mix to a purely hydro-based country can be up to 4 t CO_2-e, when an NMC lithium ion battery is considered (253 kg weight and 26.6 kWh energy capacity).

Life-cycle analysis — a look into the key parameters affecting life-cycle CO_2 emissions of passenger cars

Figure 3: Sensitivity analysis with respect to the source of electricity for battery cell manufacture (results include production and manufacturing). Impact category: global warming potential (2013 data)



NB Suffix '100' refers to 100 years.

Impact of fuel consumption (ICEs) and electricity mix (BEVs)

Life-cycle phases — definition of terms

When an LCA is applied to a vehicle, it includes the CO_2 emissions from manufacturing and disposing of the vehicle itself, as well as the CO_2 emissions from producing and supplying the fuel to the vehicle and consuming the fuel in the vehicle.

The CO_2 emissions from producing and supplying the fuel to the vehicle are referred to as well-to-tank (WTT) emissions, while the CO_2 emissions from consuming the fuel in the vehicle are referred to as tank-to-wheels (TTW) emissions. For BEVs, when only the TTW CO_2 emissions are accounted, the BEV is considered as a zero-CO_2 vehicle due to the absence of tail pipe emissions. However, the WTT approach brings additional CO_2 emissions into the whole picture, i.e. the emissions associated with the production of the electricity consumed and the energy losses from the electricity generation site to the recharging device. Besides this definition, there is currently an ongoing debate addressing how to consider the additional TTW-related losses associated with the battery recharging process, including the use of external charging devices.

Electricity mix

Currently, Europe has a wide range of electricity power generation technologies across different countries ranging from coal based national electricity mixes to mainly renewable ones. In this context, the EU electricity mix concept included in the study is considered as a reference point, while individual assessments at country level need to be conducted to produce specific scenarios that can be used to inform different stakeholders, including end users, about the LCA CO_2 performance of different alternatives.

Based on the assumptions mentioned in Table 2 (page 19), Concawe has conducted LCA-based comparisons of the CO_2 emissions of a compact class (C-segment) vehicle, for both BEV and ICE, where the impact of the national electricity mix on the use phase is explored (see Figure 4).

Figure 4: The impact of national electricity mix on the use phase of two C-segment vehicles: Nissan Leaf (BEV) vs Nissan Pulsar (diesel ICE)—1 battery/150,000 km

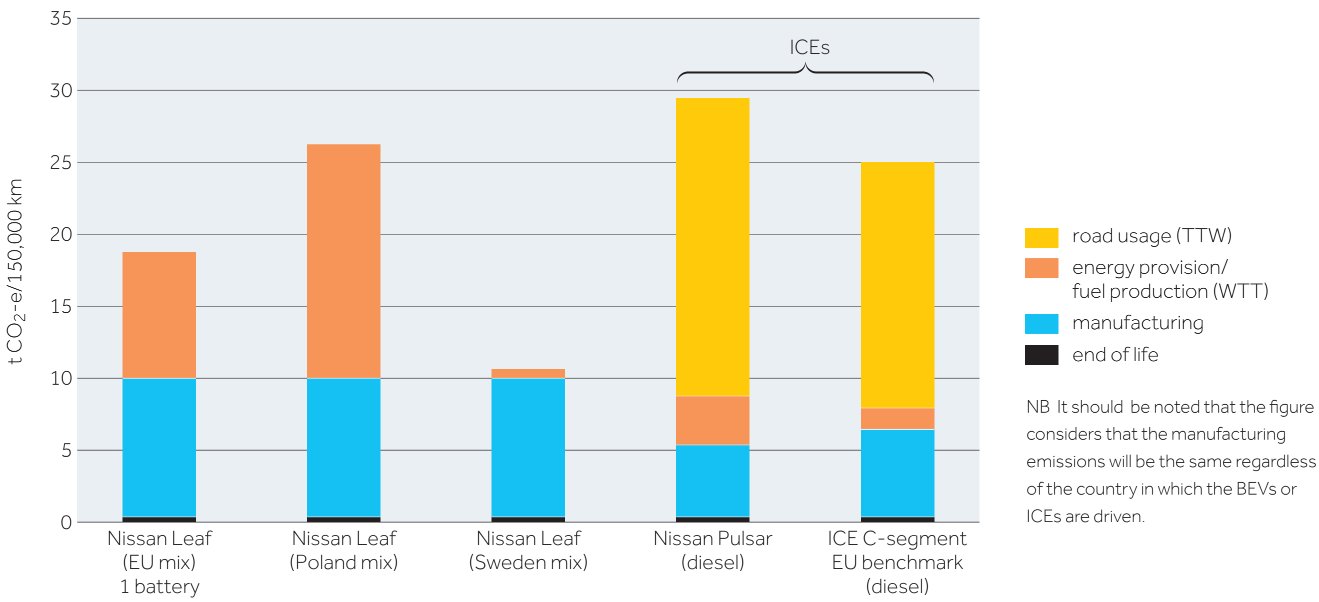


Table 4: Specific inputs: C-segment

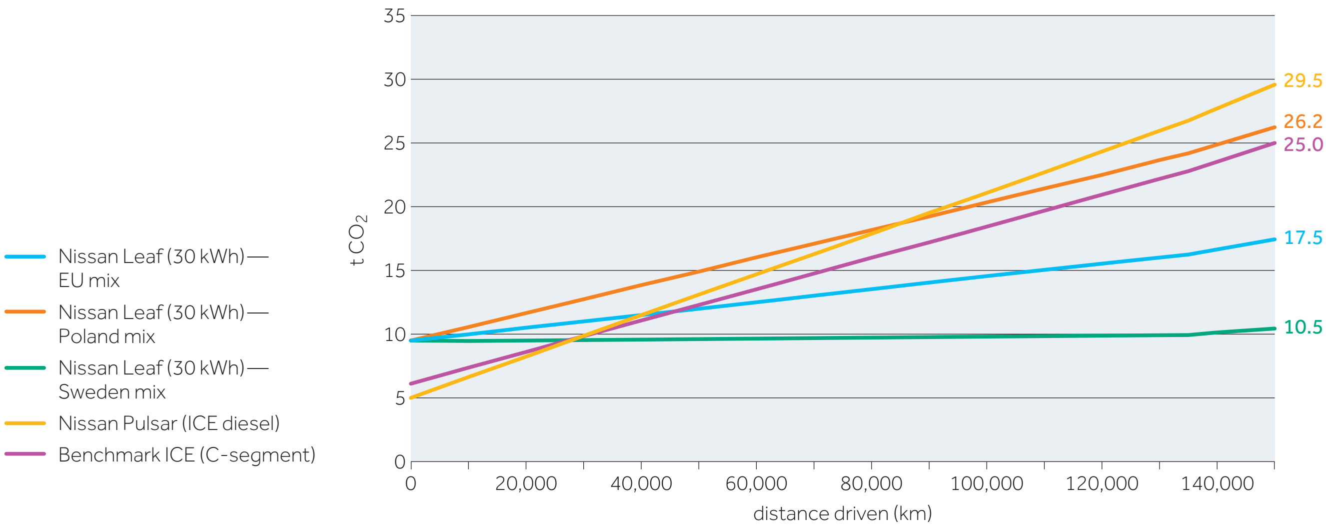
	CONSUMPTION AND WEIGHT*	BATTERY SIZE AND RANGE	CO_2 INTENSITY OF ELECTRICITY MIX
Nissan Leaf (BEV), 109 hp	150 Wh/km (without losses) Kerb weight: 1,570 kg	30 kWh battery 250 km driving range	EU mix (350 g CO_2/kWh) Higher range: Poland mix (750 g CO_2/kWh) Lower range: Sweden mix (20 g CO_2/kWh)
Nissan Pulsar (diesel ICE), 110 hp	3.8 l/100 km (NEDC) (Kerb weight: 1,352 kg)		

* Data from Nissan brochures

This comparison shows that the total amount of CO_2 emitted during the lifetime of a Nissan Pulsar (diesel) can be similar to the Nissan Leaf (BEV) when the electricity mix includes a large fraction of coal powered generating plants, as in Poland. When the Nissan Leaf is compared to the C-segment benchmark data published by the European Commission, the lifetime CO_2 emissions for the Nissan Leaf are greater than for the diesel vehicle for the stated electricity mix.

Although Figure 4 shows the contribution of each stage to the total CO_2 emissions, the evolution of the emissions along the driven distance during the whole lifetime of the vehicle leads to interesting conclusions (see Figure 5).

Figure 5: The impact of national electricity mix per distance driven for two C-segment vehicles: Nissan Leaf (BEV) vs Nissan Pulsar (diesel ICE)



At the beginning of the life of the vehicles, the BEVs have embedded emissions that are double those of the equivalent ICE powertrains, due to the battery manufacturing process. Once in use, and during the first 50,000 km driven, the emissions from the diesel fuelled vehicle (based on the C-segment benchmark vehicle) would remain lower than the overall emissions from a BEV when the anticipated 2030 EU average electricity mix is considered. The CO_2 emissions for the diesel vehicle can remain lower than for the Nissan Leaf from 30,000 to greater than 150,000 km, depending on the electricity mix used.

Over the full life cycle of the vehicle, the emissions from the use of an electric vehicle are eventually lower than those from an equivalent ICE powertrain vehicle, except in countries with a high reliance on coal. However, it is clear that on such an LCA basis, there are CO_2 emissions from the production and use of electric vehicles which should be taken into account in any assessment of the potential for electric vehicles to contribute to global GHG emission targets.

Size of the vehicle

The LCA methodology allows the comparison of different powertrains across different vehicle segments, from a small B-class vehicle to a larger D-class or a luxury one. In 2016, NTNU presented the concept of the 'fossil envelope' [8] which shows that the total CO_2 emissions are heavily dependent on the size of the vehicle/battery chosen. Therefore, a comparison between individual vehicles belonging to the same segment is crucial to conduct a comprehensive LCA.

a) Small vehicles (B-segment)

The category of 'subcompact' vehicles comprises a wide range of vehicles with power and weights similar to some of those considered as 'compact' vehicles. In this analysis, a Mercedes Benz B-Class and BMW i3 were initially chosen as representatives of this BEVs 'B' classification. However, the weight of the Mercedes Benz B-Class (1,700 kg) was more similar to a 'C' classification vehicle and, therefore, the comparison is focused on the BMW i3 (1,300 kg) with a 33 kW battery package. All these vehicles have higher power than equivalent ICE B-segment vehicles where consumers may opt for better fuel efficiency (smaller size) in less powerful vehicles than in other segments. Actually, this customer choice between more powerful vs more efficient vehicles is a constant across all the passenger car classes but it is especially important in the B-segment where higher fuel efficiencies can be achieved. Figure 6 compares the BMW i3 (one of the smaller BEVs in the market) with the Mercedes B-Class and a Renault Clio IV B-segment ICE vehicles.

When the same approach described in Figure 5 is applied to these subcompact vehicles, the break-even points for a BEV are between 20,000 and 60,000 km, usually sooner than for the C-segment vehicle but depending heavily on the electricity mix and the power of the ICE vehicle chosen. In cases where a lower-HP ICE B-segment vehicle is chosen (e.g. the Renault Clio IV), the life-cycle emissions are less than those of a BEV with a Polish electricity mix.

Figure 6: The impact of national electricity mix per distance driven for three B-segment vehicles: BMW i3 (BEV) vs Mercedes Benz B-Class (diesel ICE) vs Renault Clio IV GrandTour (diesel ICE)

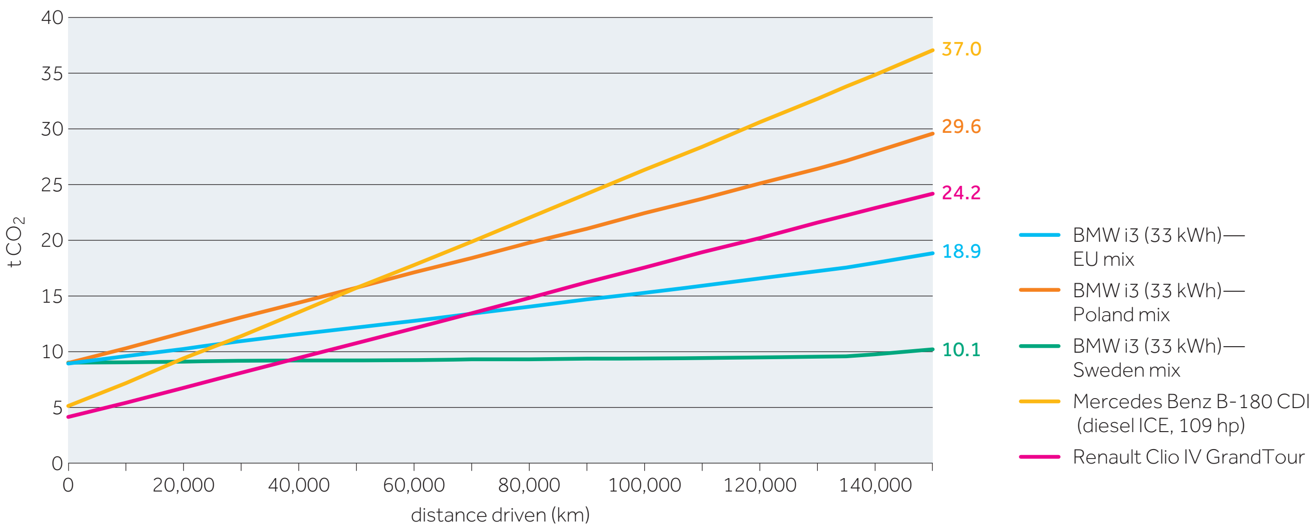


Table 5: Specific inputs: B-segment

	CONSUMPTION AND WEIGHT*	BATTERY SIZE AND RANGE	CO_2 INTENSITY OF ELECTRICITY MIX
BMW i3 (BEV)	161 Wh/km (without losses) Kerb weight: 1,300 kg	33 kWh battery 180 km driving range	EU mix (350 g CO_2/kWh) Higher range: Poland mix (750 g CO_2/kWh) Lower range: Sweden mix (20 g CO_2/kWh)
Renault Clio (diesel ICE)	3.2 l/100 km (NEDC) (Kerb weight: 1,200 kg)		
Mercedes Benz B-180 (diesel ICE), 109 hp	3.6 l/100 km (NEDC) (Kerb weight: 1,395 kg)		

* Data from Mercedes brochures

b) Large vehicles (D-segment/best-in-class)

In the case of large vehicles, the embedded emissions associated with the manufacturing stage increase significantly due to the combination of the larger sizes of both of the vehicle and the battery used to increase the driving range (representing ≈45% of the total CO_2 emissions in the selected BEV example). The location of the battery manufacturing and assembling facilities has a large impact on lifetime emissions in this vehicle segment. Also, due to the higher embedded CO_2 emissions for these D-segment BEVs, and as the vehicles in this segment are typically used to drive longer distances on more frequent journeys, ensuring that no battery replacement would be required along their lifetimes becomes the key factor in the comparison versus an equivalent ICE vehicle.

Assuming that only one battery is used, a BEV consuming an electricity mix close to the EU mix would need to be driven more than 100,000 km to reach the crossover point at which both powertrains reach parity in CO_2. When a Polish electricity mix is used, the analysis shows that an ICE diesel vehicle emits less CO_2 than a BEV during its whole lifetime.

Figure 7: The impact of national electricity mix and battery replacement on the use phase of two D-segment vehicles: Tesla Model S (BEV) vs Audi A4 (diesel ICE)—150,000 km

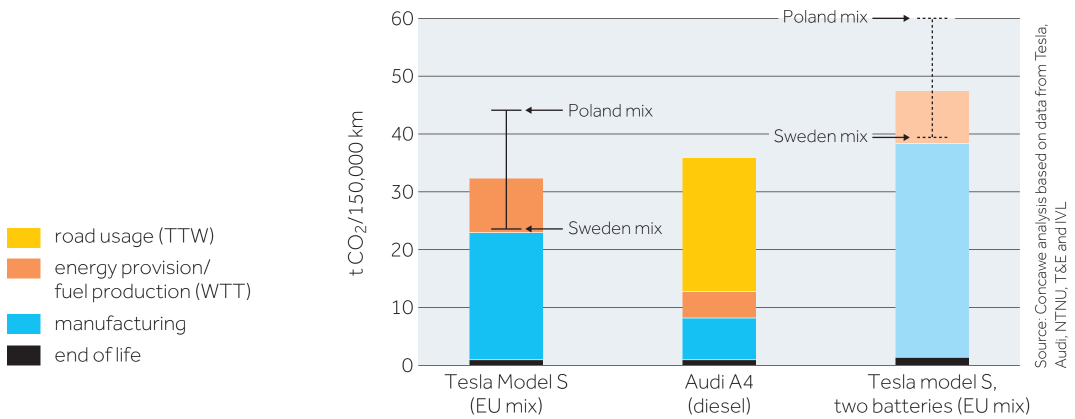


Figure 8: The impact of national electricity mix per distance driven for two D-segment vehicles: Tesla Model S (BEV) vs Audi A4 (diesel ICE)

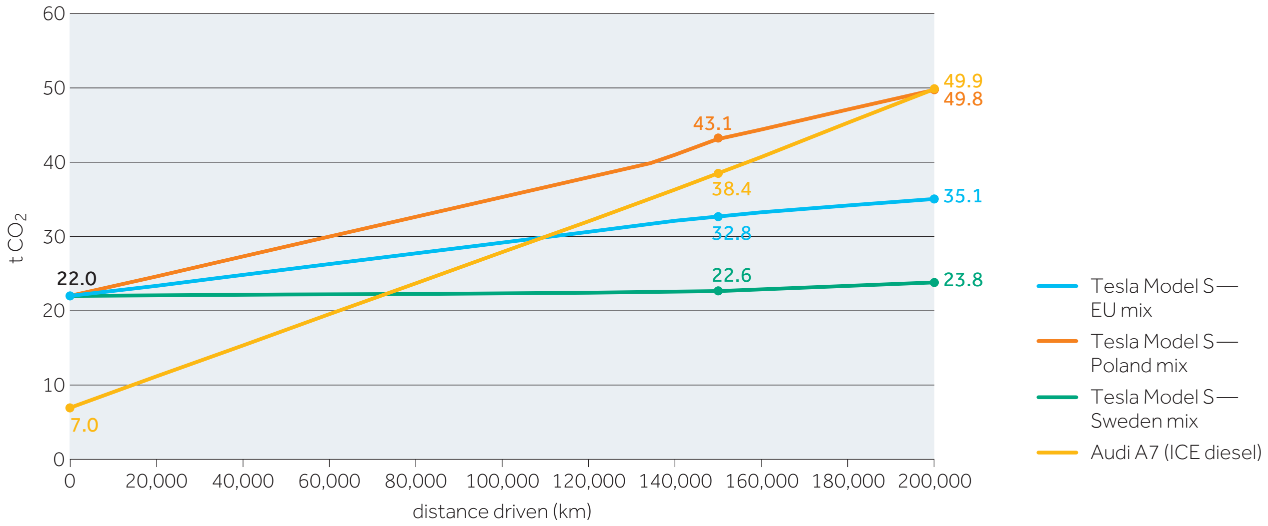


Table 6: Specific inputs: D-segment

	CONSUMPTION AND WEIGHT*	BATTERY SIZE AND RANGE	CO_2 INTENSITY OF ELECTRICITY MIX
Tesla Model S (BEV)	181 Wh/km (without losses) Kerb weight: 2,100 kg	100 kWh battery > 250 km driving range (NTNU value)	EU mix (350 g CO_2/kWh) Higher range: Poland mix (750 g CO_2/kWh) Lower range: Sweden mix (20 g CO_2/kWh)
Audi A7 3.0 TDI (diesel ICE)	4.7 l/100 km (NEDC) (Kerb weight: 1,800 kg)		

* Data from Tesla and Audi brochures, blogs and NTNU data

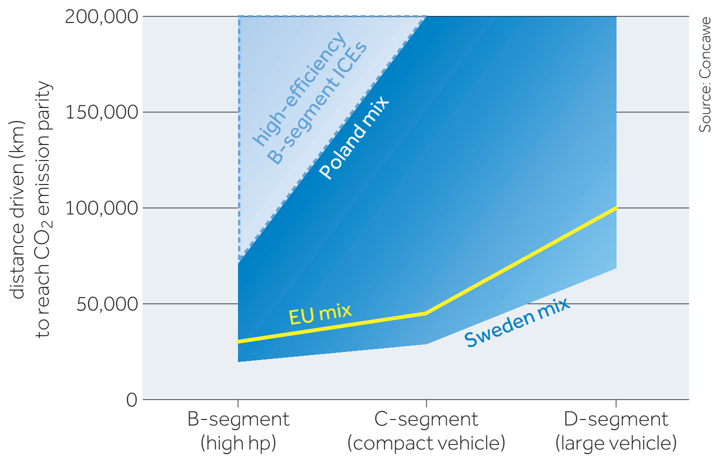
c) The electricity envelope

Figure 9 on page 28 shows the minimum distance that a vehicle would need to be driven to reach CO_2 emission parity between a BEV and an ICE powertrain for different electricity mixes, similar to the fossil fuel envelope developed by NTNU for ICE vehicles. The concept of an electricity mix envelope can be applied to explore the importance of the carbon intensity of the electricity mix consumed by BEVs.

This type of figure at a national level could help to inform different stakeholders, including consumers and policymakers, of the best available options, considering vehicle class, battery manufacturing locations and expected distance driven.

Life-cycle analysis—a look into the key parameters affecting life-cycle CO_2 emissions of passenger cars

Figure 9: Example of an electricity mix envelope based on selected vehicles



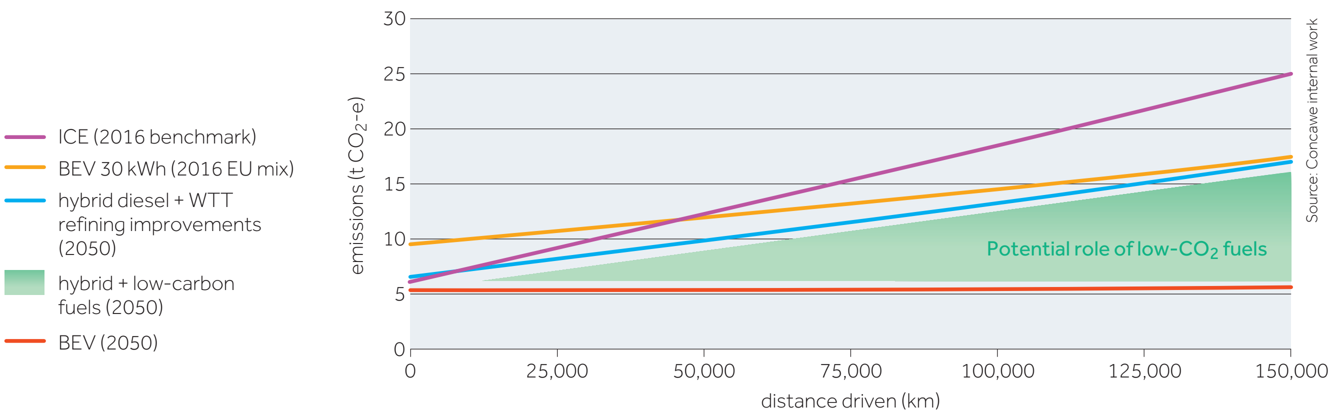
Fuel consumption: the role of low-carbon liquid fuels

Concawe is also exploring how future high efficiency internal combustion engine technologies, combined with low-carbon fuels, have the potential to deliver significant CO_2 savings.

To guide future research and policy, the same LCA analyses can be developed to assess the mitigation potential of different pathways. As shown by the green area in Figure 10, the combination of ICE and hybridisation has the potential to provide life-cycle CO_2 emission savings comparable with forecasted figures for future improved BEVs powered by electricity generated mainly using renewable sources (red line).

Ricardo is currently conducting an analysis assessing the LCA emissions associated with low-carbon fuels combusted in the most efficient internal combustion/hybrid vehicles.[1] The preliminary results confirm that, by 2050 for certain advanced biofuels and power-to-liquid technologies, the combination of highly efficient ICE powertrains and lower-carbon fuels are likely to give similar reductions in life-cycle CO_2 emissions when compared with BEV vehicles powered by a highly decarbonized electricity mix.

Figure 10: The potential role of low-carbon fuels in an LCA (conceptual approach)



Conclusions

This is the first published article associated with Concawe's ongoing research on life-cycle analysis and the potential role of low-carbon fuels that is being undertaken as part of the long-term strategy of the refining industry.[9,10] Several conclusions can be drawn from the results presented:

- Methodology:
    - LCA is a scientifically sound, well accepted methodology allowing the comparison of different powertrains on the same basis.
    - Currently, there is a need for more data from manufacturers, especially regarding batteries, to improve the accuracy of the LCAs conducted in the transport sector, and a recognised standardised basis for conducting LCAs.
    - Comparisons should be performed at the country level and by vehicle classification to provide meaningful results.

- Results:
    - When comparing electric vehicles with conventional powertrains, the relative contribution to the total life-cycle emissions associated with the different phases of energy or fuel generation, materials extraction, manufacturing and production all need to be included.
    - The energy mix used during the battery manufacturing process has a significant impact on the total CO_2 emitted during the life of the vehicle.
    - The carbon intensity of the electricity mix used to recharge the vehicles has a strong influence on the life-cycle emissions of electric vehicles.
    - The break-even distance for the life-cycle CO_2 emissions of electric vehicles compared to conventional vehicles is dependent on the vehicle size as well as the electricity mix. B-segment vehicles have the shortest break-even distance, while D-segment vehicles have the longest break-even distance. For an electricity mix that is heavily dependent on coal and heavier vehicles, the life-cycle CO_2 emissions of electric vehicles will be greater than for conventional vehicles.
    - Future high-efficiency ICE technologies, combined with low-carbon fuels, have the potential to deliver significant CO_2 savings across all segments, similar to BEVs using a largely renewable-based electricity mix.

Finally, the vehicles presented in this study are examples chosen to illustrate the main concepts of the LCA methodology, stressing the importance of different parameters in the final CO_2 emissions associated with each powertrain considered.

Concawe is willing to engage with external stakeholders to assist in developing a standard LCA methodology specifically for analysing future fuels and powertrains.

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Interview with Dr Mike Spence, Concawe's Science Executive for Water, Soil and Waste and Oil Pipelines

Mike Spence joined Concawe in 2014. As his work with Concawe draws to a close, Mike shares with us some of the aspects of his work experience as Science Executive over the past four years.

Dr Mike Spence talks about his experience as Science Executive at Concawe.

Q: Mike, you worked for Concawe as Science Executive for Water, Soil and Waste and Oil Pipelines; how did you learn about this opportunity and what attracted you to taking on this position?

A: *I heard about the Concawe opportunity in April 2014 from Graham Whale, who is the Chair of the Water, Soil and Waste Management Group. I thought this role could be a great career development opportunity and will provide me with experience in research programme management, participation in EU policy making and experience in working on projects with experts from refineries across Europe. As my research background is in groundwater and environmental fate assessment this was also a great opportunity to extend my research experience into new areas.*

Q: You then accepted the position of Science Executive for Water, Soil and Waste and Oil Pipelines; how did you find this new challenge?

A: *Once I'd accepted the position a lot needed to happen very quickly! The interview was in mid-April and by 27 July we had moved from the UK to our new home in Brussels, ready to start work on 1 August. Thankfully August is a quiet period in Brussels and so I had a few days to read up on the work of my predecessors and learn the Concawe systems and processes. As with any new role the first challenge is to meet with colleagues and stakeholders, and in Concawe there are a great many of these. I also had to get to work on developing presentations for the upcoming Concawe Symposium in February 2015, and managing the contracting and delivery of the 2014 research projects.*

Q: What did you appreciate most about your Concawe assignment?

A: *The management groups at Concawe span the full range of environmental sciences relevant to downstream operations, and so you are working with senior experts in practically every area of technical expertise. You develop over time a very integrated understanding of the issues facing the sector and how they are being addressed, which is a unique advantage of working in Concawe. The Association is also a great place to get things done due to it's small size, wide range of in-house expertise and excellent local administrative support.*

Q: Can you tell us about the key projects you have been working on as Science Executive during your time at Concawe?

A: *The main water project that comes to mind is the development of a new web-based survey of EU refinery water use and discharges to the environment. Previously this data was collected using spreadsheets, which made it difficult to understand the flows of water through a refinery and the extent to which water is recycled. The new system guides users through the data entry step-by-step and includes built-in checks on the site water balance, as well as providing sites with a summary report on their water use. For the oil pipelines management group Concawe convened a special seminar on illegal tapping in March 2016 to address a rapid rise in the annual number of theft incidents, which alerted operators to the risks and possible control measures.*

Interview with Dr Mike Spence, Concawe's Science Executive for Water, Soil and Waste and Oil Pipelines

Q: Can you explain in a few words why the work and studies conducted by Concawe are so valuable for its members?

A: *Concawe adds great value for its member companies by providing sector-level feedback to policymakers so that the full impact of policy decisions is made clear. The role of Concawe has become increasingly important in recent years due to a reduction in the number of technical experts working in the member companies. In Concawe the remaining experts can work cross-sector to deliver complex, cutting-edge research projects that no single company would be able to manage. In addition, Concawe is recognised for scientific excellence, and so is highly influential in science and policy debate. Concawe, together with FuelsEurope, can also support member companies in their interpretation of European Legislation, for example to support dialogue with national regulators on technical matters and to clarify what is required at the EU level.*

Q: Many research associates have joined the Association recently; how have they helped you in your everyday work?

A: *The introduction of the research associates (and highly proficient interns) has been a massive benefit for the Science Executives who now have more time to address the strategic aspects. They provide continuity in terms of knowledge retention, and bring new skills, life and energy to the Association, which is great!*

Q: Looking into the future, what are the main challenges ahead for your successor?

A: *Alongside the ongoing REFIT review of the Water Framework and related directives, the Commission has launched a number of studies and initiatives that could lead to significant changes in the way refineries manage water resources. These could include measures around water pricing, water reuse and new effect-based approaches to the assessment of discharge quality. In addition, there are signs that future BREF revisions may require much greater preparation in terms of data gathering, which may be difficult to manage given limited member company resources. The challenge will therefore be to anticipate such developments well ahead of time, so that the Association is ready to respond when needed.*

Q: How has your experience at Concawe helped you in your career / how do you believe it might help you in your career?

A: *I would say it has helped in many ways. For example, it has given me the confidence to lead a large programme of research activities and improved my communication skills. It has also broadened my technical expertise and knowledge of technical challenges facing refineries across Europe. I've also gained team management skills that would not be available in a technical role outside the Association.*

Q: Would you recommend that your colleagues undertake a similar development path?

A: *I would certainly recommend a Concawe role, both in terms of the unique experience it provides and the great working environment. You get a great deal of autonomy as a Science Executive, which is great for the successful planning, management and delivery of research projects.*

Q: Do you expect a significant evolution in Concawe's Water, Soil and Waste and Oil Pipelines science in the future?

A: *Significant changes can be envisaged driven by the ongoing EU initiatives for increased resource efficiency, reduced emissions and discharges, and increased use of renewable energy resources. In particular the work of WSWMG [Water, Soil and Waste Management Group] could change if there is a big increase in the refining of fuels from renewable energy resources (e.g. biomass or e-fuels) rather than petroleum.*

Q: What did you enjoy the most about your Brussels assignment?

A: *My family and I have really enjoyed living and working in Brussels. The city is quite compact and you only need to go 15 km from the centre to find open countryside with fields, woodlands and quiet cycle routes. It also has excellent rail and air transport links making most European destinations within easy reach.*

The importance of carbon capture and storage technology in European refineries

This article describes the importance of carbon capture and storage (CCS) in meeting future emission targets. It presents an evaluation of the costs of retrofitting CCS technology in a range of existing refineries, and considers the reasons why these estimates are significantly larger than the estimated costs of CO_2 capture for other sources, e.g. power generation, cement and steel production, etc.

Background

For the first time in history, at the Conference of the Parties (COP 21) in December 2015, the world agreed to set an ambitious target. The headline emerging from the summit was the agreement to limit the increase of the global average temperature to well below 2°C, and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels.[1]

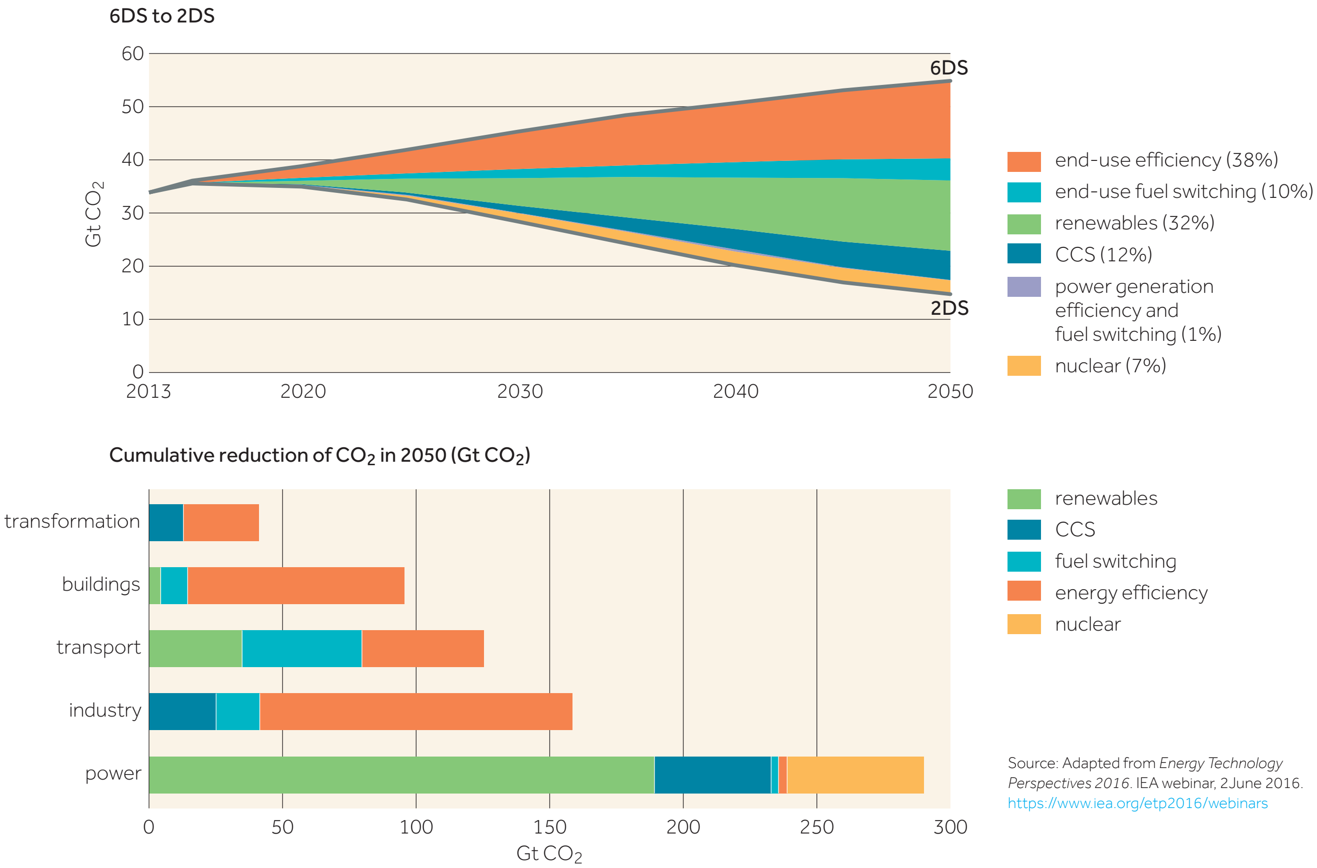
Carbon capture and storage (CCS) is an essential element of the portfolio of measures needed to reduce greenhouse gas (GHG) emissions. Without CCS, the cost of reaching the COP 21 targets will increase by about 40%[2] which is more costly than for any other low-carbon technology. CCS is a key technology to reduce CO_2 emissions across various sectors of the economy while providing other societal benefits (energy security and access, air pollution reduction, grid stability, and jobs preservation and creation). It is part of a broad range of measures aimed at reducing CO_2 emissions.

Until recently, CCS projects in Europe were mainly targeted at reducing GHG emission from the power sector, where some of the largest emissions points are found. The past few years have seen significant changes in the power sector in Europe, including increased penetration of renewable energy, a rapid phase-out of coal-fired power plants in several Member States, a fuel switch from coal to gas, and the emergence of nuclear power in Member State plans for medium-term reform of the energy system.

The International Energy Agency (IEA) describes three pathways for energy sector development to 2060. The Reference Technology Scenario (RTS) provides a baseline scenario that takes into account existing energy- and climate-related commitments by countries. The RTS—reflecting the world's current ambitions—is not consistent with achieving global climate mitigation objectives, but would still represent a significant shift from a historical 'business as usual' or 'current trajectory' approach (the '6°C Scenario'—6DS). More ambitious decarbonisation requires increased effort and sustained political commitment.

While COP 21 sets the 'must achieve' target at a maximum 2°C increase, a more ambitious 'stretch' target of 1.5°C was also agreed. This is reflected in the IEA's 'Beyond 2°C Scenario' (B2DS). Each scenario sets out a rapid decarbonisation pathway in line with international policy goals (see Figure 1 on page 35).

Figure 1: Contribution of technology area and sector to global cumulative CO_2 reductions



Source: Adapted from *Energy Technology Perspectives 2016*. IEA webinar, 2June 2016. https://www.iea.org/etp2016/webinars

To achieve the IEA 2DS, reductions of 740 Gt CO_2 (relative to RTS) would be required from the application of energy efficiency, renewables, nuclear, CCS and fuel switching. The technology scenarios would see the power sector decarbonised earliest, leaving industry and transport as the major emitters by 2050. In the 2DS, half of the captured CO_2 would come from industrial sectors, where there are currently limited or no alternatives for achieving deep emission reductions.

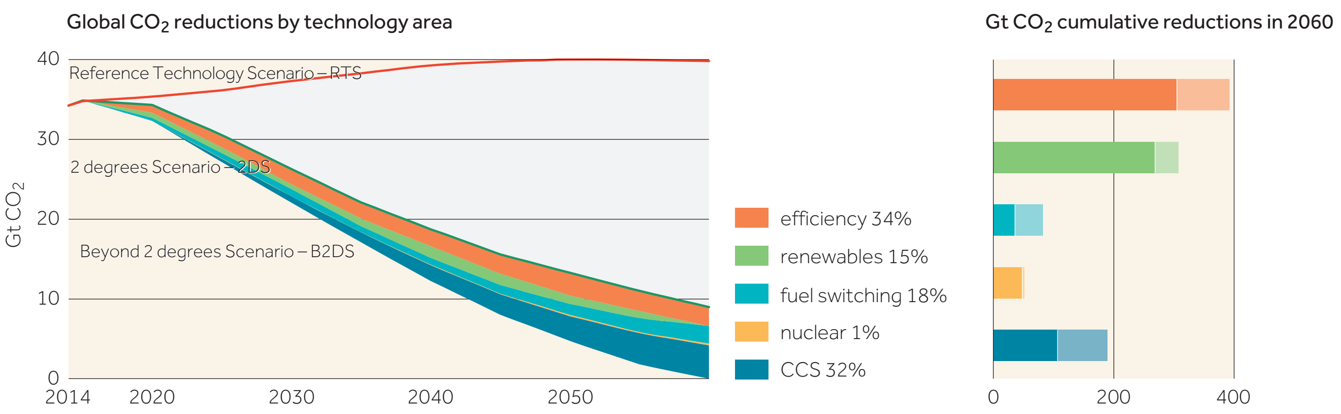
Such a transition will require an exceptional degree of effort. The share of fossil fuels in primary energy would have to reduce to 45% by 2050 in the 2DS (compared to 81% today). In this scenario, biomass becomes the largest energy source (for transport).

To achieve net zero emissions in the second half of the century, bioenergy with CCS (BECCS) has the potential to deliver negative emissions. The technology scenarios supported by IEA projections are illustrated in Figure 2 on page 36 which shows that:

- CCS will be required to achieve 12 to 15% of the reductions needed for 2DS.
- CCS will be required to achieve 32% of the additional reductions needed for B2DS.
- By 2060 the storage needed for industrial applications could equal that of power generation.

The importance of carbon capture and storage technology in European refineries

Figure 2: Technology area contribution to global cumulative CO_2 reductions

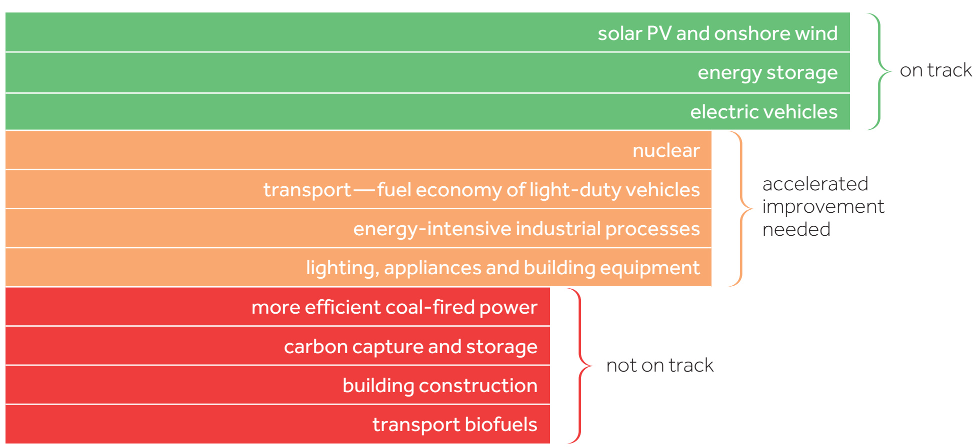


Source: *Adapted from Energy Technology Perspectives 2017*. IEA webinar, 2 July 2017. https://www.iea.org/etp2017/webinars

The agreement at COP 21 to pursue a more stringent target than the previous 2°C limit has strengthened the case for a need of deep-cut technologies such as CCS. Deep reductions are needed, not only in the power sector but also for the industry, where decarbonisation options are limited. GHG emission reductions from carbon-intensive industries will require carbon capture because fuel switching is often not an option, or process-related emissions cannot be avoided. Meeting the national emission reduction targets by 2030 will rely heavily on reducing emissions from carbon-intensive sectors such as steel and refining.

In the IEA's *Energy Technology Perspectives 2017*,[3] the organisation highlighted that the recent progress in some clean energy areas is promising, but many technologies still need a strong push to achieve their full potential and deliver a sustainable energy future. The potential of clean energy technology remains underutilised (see Figure 3).

Figure 3: Many technologies still need a strong push to achieve their full potential to deliver a sustainable energy future



Source: *Adapted from Energy Technology Perspectives 2017*. IEA webinar, 2 July 2017. https://www.iea.org/etp2017/webinars

The importance of deploying CCS and the industry sector

In 2014 the global total energy-related direct emissions of CO_2 amounted to approximately 34,200 megatonnes (Mt), of which 8,300 Mt CO_2/year were direct emissions from industry and 13,600 Mt CO_2/year were direct emissions from the power sector.[3] To reach the Paris Agreement's 2°C target, the IEA estimated that global CO_2 emissions must be reduced to just below 9,000 Mt CO_2/year by 2060, a reduction of more than 60% compared to 2014, and must fall to net zero by no later than 2100.[3]

In the IEA's 2DS, CCS will account for 14% of the accumulated reduction of CO_2 emissions by 2060 and 32% of the reduction needed to go from 2DS to B2DS by 2060.[3] Major cuts will need to be made in all sectors in addition to the power sector. The industrial sector will have to capture and store 1,600 Mt CO_2/year in 2DS and 3,800 Mt CO_2/year in B2DS by 2060, yet this sector will still be the largest contributor to accumulated CO_2 emissions to 2060, and the major CO_2 source in 2060.

CCS is already being undertaken in industries such as natural gas processing, fertilizer production, bioethanol production, hydrogen production, coal gasification, and iron and steel production.[4] In addition, the demonstration of a CO_2 capture unit at a waste incineration plant has taken place in Japan,[5] and small-scale testing has taken place in Norway.[6] In 2060, CCS is expected to make up 38% of total emissions reductions in industry between RTS and B2DS, and somewhat less than half this amount between RTS and 2DS;[3] this shows that CCS will be a critical technology for many emissions-intensive industries.

There is a high likelihood that 2DS and, in particular B2DS, wil not be achievable without the deployment of 'negative emissions technologies' at scale.[7,3] There are several technologies that have the potential to contribute to the reduction of atmospheric CO_2 levels; each of these, however, brings its own uncertainties, challenges and opportunities. Included among them are reforestation, afforestation (photosynthesis), direct air capture, and bioenergy coupled with CCS (i.e. CCS applied to the conversion of biomass into final energy products or chemicals). In B2DS, almost 5,000 Mt CO_2 are captured from bioenergy, resulting in negative emissions in 2060.[3]

CO_2 capture technology

CO_2 capture is a process that involves the separation of CO_2 from gas streams. These gas streams could include, but are not limited to, combustion flue gases, process off-gases (i.e. by-product gases from blast furnaces and basic oxygen furnaces; tail gases from steam methane reforming and various refinery processes, etc.), syngas (i.e. synthesis gas produced from coal gasification, hydrocarbon reforming, coke oven, etc.) or natural gas (i.e. from natural gas processing). For many decades, CO_2 capture processes have been used in several industrial applications at a scale close to those required in CCS applications.

In general, CO_2 capture processes can be classified according to their gas separation principle, namely chemical absorption, physical absorption, adsorption, calcium and reversible chemical loops, membranes, and cryogenic separation.

In the ReCAP project (see below), the chosen technology was a chemical absorption process. It utilizes the reversible chemical reaction of CO_2 with an aqueous solvent, usually an amine or ammonia (MEA in this case). CO_2 is separated by passing the flue gas through a continuous scrubbing system. The absorbed CO_2 is stripped from the solution in a desorber, and a pure stream of CO_2 is sent for compression while the regenerated solvent is sent back to the absorber.

The oil refining industry

On a global level, the total CO_2 emitted by mainstream refineries in 2015 was estimated to be around 970 Mt per year.[8] The total processed crude oil was ~82 Mb/d (total capacity ~97.5 Mb/d) which results in a CO_2 intensity of around 200 kg CO_2/t crude oil. This intensity varies for each refinery and depends on the complexity, energy efficiency and ratio of feedstocks other than crude oil.

The global refining sector contributes around 4% of the total anthropogenic CO_2 emissions. CCS has been recognised as one of the technologies that could be deployed to achieve a deep reduction of greenhouse gas emissions in this and other industry sectors.

In the EU-28, the verified emissions from the 79 mainstream refineries were 138 Mt CO_2/y in 2015 (~14% of the world emissions from refineries). Today, the EU refining industry has reduced its environmental footprint by continually increasing its energy integration and investments in efficiency. Moreover, the widespread use of cogeneration and advanced catalyst technology has allowed for further energy reduction gains. As a result, the refining sector has improved its energy efficiency by nearly 1% per year since 1990.

The ReCAP project: understanding the cost of retrofitting CO_2 capture to refineries

In 2014, the ReCAP project was initiated by the IEA Greenhouse Gas R&D Programme (IEAGHG), in collaboration with GASSNOVA, SINTEF and Concawe, to evaluate the performance and cost of retrofitting CO_2 capture in an integrated oil refinery.

To enable the deployment of CCS in the oil refining sector, it is essential to have a good understanding of the direct impact on the financial performance and technical operations resulting from the retrofitting of CO_2 capture technology. In several OECD countries (especially in Europe), it is expected that no new refineries will be built in the coming decades. Furthermore, most of the existing refineries are at least 20 years old. Therefore, this study aims to evaluate and understand the cost of retrofitting CO_2 capture technologies to an existing integrated oil refinery. The project was supported under the Norwegian CLIMIT programme, with contributions from IEAGHG and Concawe and managed by SINTEF. The project consortium selected Amec Foster Wheeler as the engineering contractor to work with SINTEF in performing the basic engineering and cost estimation for the reference cases.

ReCAP project — scope of work

The main purpose of the study was to evaluate the cost of retrofitting CO_2 capture in a range of refinery types typical of those found in Europe. These included both simple and high-complexity refineries covering typical European refinery capacities from 100,000 to 350,000 bbl/d.

The refining industry is considered to be an energy-intensive industry, with direct emissions typically ranging from 100 to 200 kg CO_2/tonne crude oil. An oil refinery produces a broad range of highly valuable petroleum products using different and complex interconnected processes. While each plant is unique, the level of complexity is a common factor.

To ensure that the work could differentiate between the costs of CCS deployment for different types of refineries and those of varying capacities, four reference (model) oil refineries were evaluated:

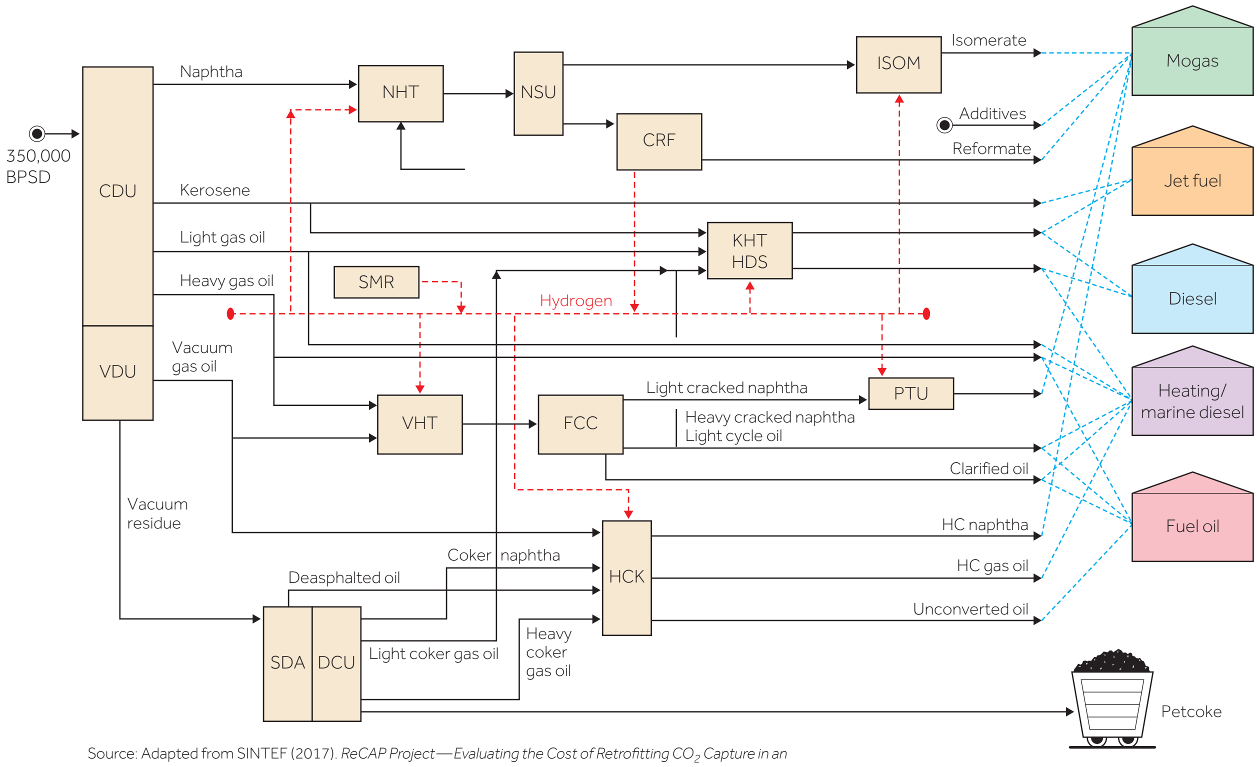
- Simple refinery with a nominal capacity of 100,000 bbl/d.
- Medium-complex refinery with a nominal capacity of 220,000 bbl/d.
- Highly-complex refinery with a nominal capacity of 220,000 bbl/d.
- Highly-complex refinery with a nominal capacity of 350,000 bbl/d.

Different scenarios presenting the cost of capturing CO_2 from the different processes within the refinery were evaluated. The priorities for which sources of CO_2 will be captured for each reference plant were defined based on the size of emissions and the plant layout, taking into account the practical considerations in deploying the CO_2 capture facilities on-site. The results established a wide range of overall refinery CO_2 capture ratios, and provide insights into their respective costs of CO_2 avoidance.

The analysis is based on a 'bottom up' approach to reflect the site-specific conditions and to identify what could likely be achieved in terms of CO_2 reduction potential and the related cost of retrofitting CCS technology. The assessments performed in this study focused on retrofit costs including modifications in the refineries, interconnections, and additional combined heat and power (CHP) and utility facilities.

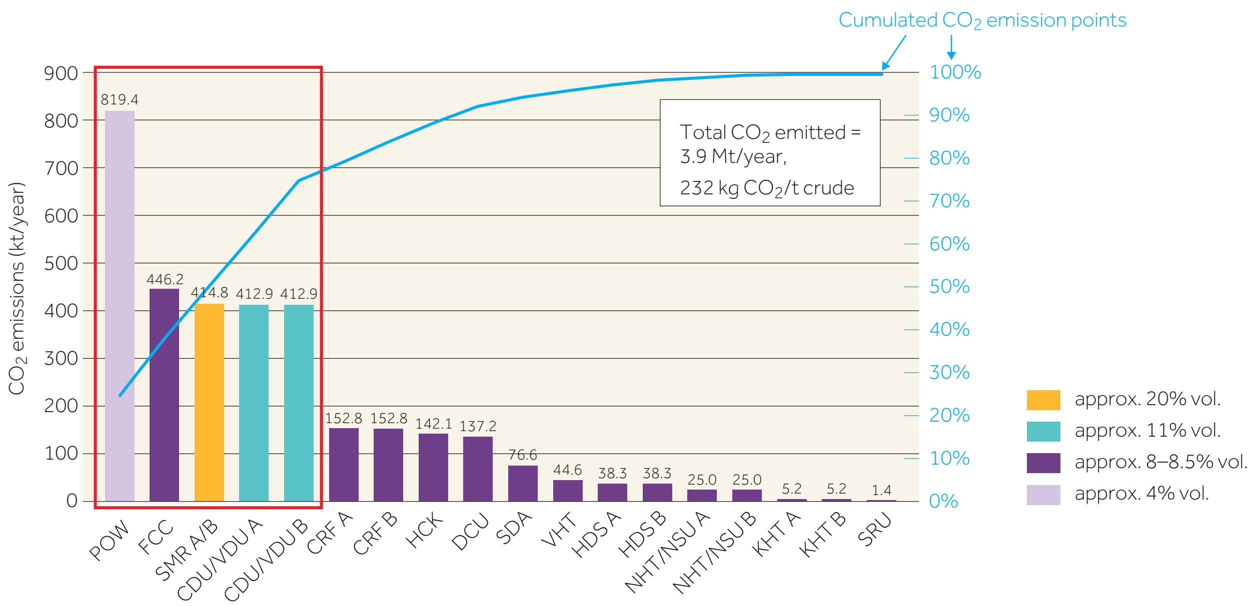
Figure 4 on page 40 presents a simplified flow diagram of a typical complex refinery with more than 10 emission sources. Figure 5 on page 40 shows that five of these sources represent 75% of the total CO_2 emitted. The CO_2 concentration fluctuates between 5% and 20% vol.

Figure 4: Simplified flow diagram for a typical complex refinery



Source: Adapted from SINTEF (2017). *ReCAP Project—Evaluating the Cost of Retrofitting CO_2 Capture in an Integrated Oil Refinery: Description of Reference Plants*. https://www.sintef.no/recap

Figure 5: The main CO_2 emission sources for a typical complex refinery with a nominal capacity of 350,000 bbl/day



Source: Adapted from SINTEF (2017). *ReCAP Project—Evaluating the Cost of Retrofitting CO_2 Capture in an Integrated Oil Refinery: Description of Reference Plants*. https://www.sintef.no/recap

Refinery base cases

Four refinery base cases were defined to represent the typical crude mix and product slate of similar-capacity European oil refineries:

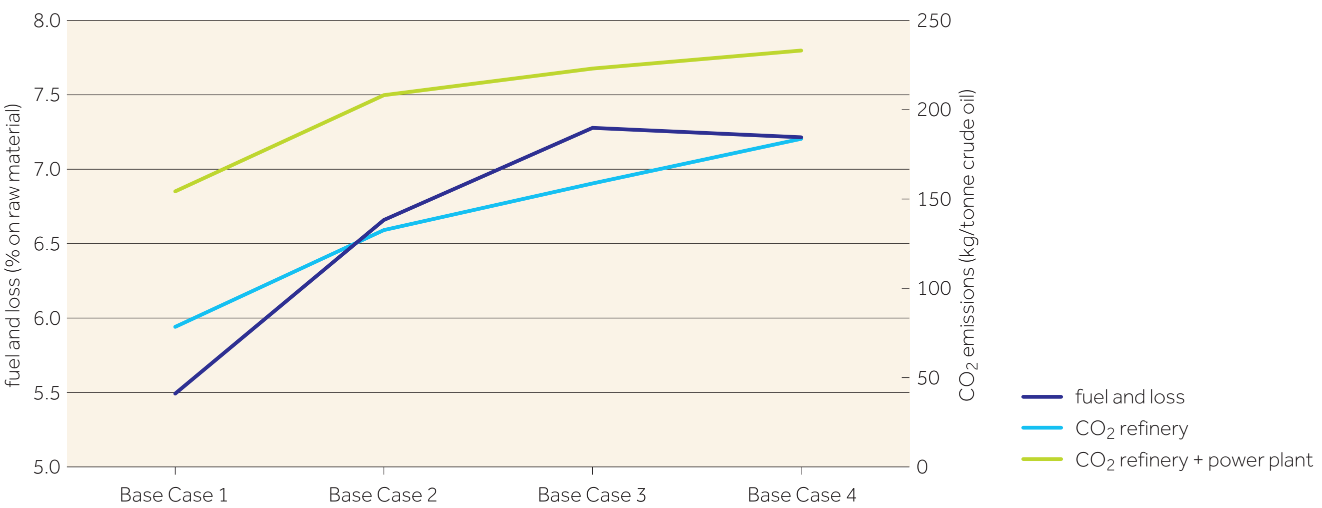
- Base Case 1 (BC1)—a simple hydroskimming refinery.
- Base Case 2 (BC2)—a medium complexity refinery that is a retrofit of BC1.
- Base Case 3 (BC3)—a complex refinery that is a retrofit of BC2.
- Base Case 4 (BC4)—a large complex oil refinery.

As the complexity of the refinery increases from BC1 to BC4, the yield of naphtha and gas oil fraction increases as the heavy cuts are converted into lighter and more valuable products in the more complex refineries.

The performance of the refinery base cases, in terms of mass and energy balances and CO_2 emissions, are the basis for comparison of the effectiveness and cost of oil refineries with CO_2 capture. The market conditions in the past decade have pushed the refineries to upgrade their configuration to process heavier crudes, cheaper than the lighter ones, and to reprocess heavy distillate products to obtain more valuable fractions. These energy-intensive units, however, demand a greater amount of fuel and, in turn, increase the amount of CO_2 emitted.

The four identified base cases are shown in Figure 6. These are good starting points for evaluating the effects of retrofitting CO_2 capture facilities in existing refineries, taking into account the different sizes and levels of complexity.

Figure 6: Fuel demand and CO_2 emissions in the four base case refineries



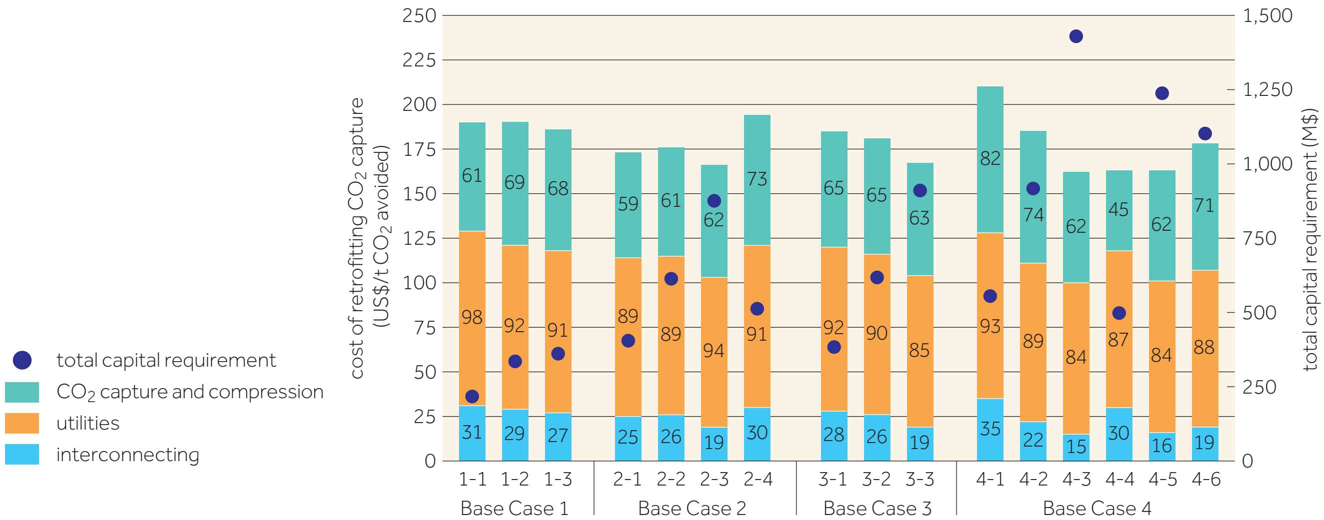
CO_2 capture integration

The focus of this study was on post-combustion capture. The primary emission sources in each base case refinery were identified, and CO_2 capture cases for the different refineries were established to explore CO_2 capture from a range of refinery CO_2 sources that vary in both capacity and CO_2 concentration. The capture cases were set up to include an absorber for each emission source and a common regenerator due to space constraints and to minimise expensive ducting in the refinery.

A total of 16 post-combustion capture cases using MEA as solvent were investigated. The MEA process for post-combustion capture has been simulated using Aspen HYSYS® (a process simulation software package) where a simple configuration with an intercooler in the absorber was modelled. The CO_2 capture process was not optimised for the different cases.

The assessments performed in the study focused on retrofit costs including modifications in the refineries, interconnections, and additional CHP and utility facilities. The main focus of the study was on CO_2 capture from refinery BC4, which was considered to be the most relevant reference for existing European refineries of interest for CO_2 capture retrofit. Considering the large number of cases (16) and their complexity, a hybrid methodology was used to evaluate the cost of the different sections (CO_2 capture and compression, utilities and interconnecting) of the concept. In this approach, four of the 16 capture cases were selected to represent a wide range of CO_2 capture capacity and flue gas CO_2 content. In each case, detailed assessments were undertaken. These detailed cost assessments form the basis for the assessment of the other cases, based on subsequent scaling. The scaling equations have a larger purpose in that they can be used by refineries/policy experts to evaluate capital costs of retrofitting CO_2 capture to refineries of interest.

Figure 7: Costs of retrofitting CO_2 capture for all cases considered for the four refinery bases cases, by section



The results of the cost evaluation of the 16 CO_2 capture cases show that the cost of retrofitting CO_2 capture lies between 160 and 210 US$/t CO_2 avoided, as shown in Figure 7 on page 42. These estimates are significantly larger than estimates available in the literature on CO_2 capture for other sources (natural gas and coal power generation, cement, steel, etc.). Three main reasons for this difference are as follows:

- The inclusion of the retrofit costs such as the costs of ducting, piping, moving tankages, etc.
- There is no synergy with the refinery. The utilities cost is based on the installation of an additional CHP plant, cooling water towers and waste water plant, which are designed with significant spare capacity in some cases (up to 30% overdesign).
- Most of the CO_2 capture cases considered include small-to-medium CO_2 emission point sources and/or low-to-medium flue gas CO_2 content (7 of the 16 cases considered include only flue gases with CO_2 content below or equal to 11.3% vol).

The overall breakdown of the costs is as follows:

- 30–40% of costs are linked to CO_2 capture and conditioning;
- 45–55% are linked to utilities production; and
- 10–20% are linked to interconnecting costs.

In terms of investment cost, the estimations show that the total capital requirement lies between US$200 million and US$1,500 million for the different cases as shown in Figure 7 on page 42, depending primarily on the amount of CO_2 captured. It is worth noting that although a case may be cheaper in terms of normalised cost ($/t CO_2 avoided), the high total capital requirements could make retrofitting less attractive.

In general, the cost of retrofitting CO_2 capture reduces with increasing CO_2 avoided, showing the effect of economies of scale. However, this may not be the case where the effects of significant differences in flue gas CO_2 concentration, the number of flue gas desulphurisation units and the interconnecting distances outweigh the effects of economies of scale.

Future development and investigation

With this backdrop, an approach with a potential to significantly decrease the cost of capture is to reduce the cost of utilities—in particular the additional CHP plant required to supply steam and power for CO_2 capture and compression. It is also desirable to avoid additional CHP plant since it reduces the rate of CO_2 capture.

Three options that may be explored, individually or in concert, to avoid the need for additional CHP plant and thus reduce the cost of CO_2 capture include the following:

1. Reduce the steam (and if possible power) requirement for CO_2 capture and compression:
   - Evaluation of advanced solvents with lower specific heat requirements, such as piperazine: such solvents may require steam at different pressures/condensing temperatures, and the reboiler/stripper may also operate at a different pressure than in the present case.
   - Use of advanced process configurations for the post-combustion capture process, including process improvements for enhanced absorption, heat integration and heat pumping. Among these options, split flow arrangements are the most common where the general principle is to regenerate the solvent at two or more loading ratios.
   - Use of technologies, such as membranes, that do not require steam: power required for the capture process can be bought in over the fence from the electricity grid.
2. Lower utilities investment costs achieved through reduced design margins. The design of CHP plant has, in some cases, been undertaken to provide significant spare capacity (up to 30%). In practice, where this additional capacity has been included to provide the steam and power required for CO_2 capture, it may be reduced.
3. Use of readily available waste heat within the refinery plant as well as (when relevant) from nearby industries, in combination with purchase of the necessary power for CO_2 capture and compression from the grid, preferably from renewable power or large efficient thermal power plants with CO_2 capture. This would most likely require performing a case study on an actual refinery, but could also be done for BC4 (the large complex refinery model).

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Abbreviations and terms

2DS 2°C Scenario

6DS 6°C Scenario

AQLV Air Quality Limit Value

B2DS Beyond 2°C Scenario

BC Black Carbon

BEV Battery Electric Vehicle

BMVI German Federal Ministry of Transport and Digital Infrastructure

BAT Best Available Techniques

BPSD Barrel Per Stream Day

BREF ***(or BAT REF)*** BAT Reference document. Full title: 'Reference Document on Best Available Techniques for ...' (A series of documents produced by the European Integration Pollution Prevention and Control Bureau (EIPPCB) to assist in the selection of BATs for each activity area listed in Annex 1 of Directive 96/61/EC).

CCS Carbon Capture and Storage

CDU Crude Distillation Unit

CESM Community Earth System Model

CF Conformity Factor

CHP Combined Heat and Power

CO_2 Carbon Dioxide

CO_2-e Carbon Dioxide Equivalent

COP 21 21^{st} Session of the Conference of the Parties to the UNFCCC

CRE Cloud Radiative Effect

CRF Catalytic ReFormer

DCU Delayed Coker Unit

DMS DiMethyl Sulphide

DOE U.S. Department of Energy

DRE Direct Radiative Effect

EEA European Environment Agency

EOL End Of Life

EU European Union

EV Electric Vehicle

FCC Fluid Catalytic Cracker

FGD Flue Gas Desulphurisation

GAINS Greenhouse Gas—Air Pollution Interactions and Synergies

GHG Greenhouse Gas

GWP Global Warming Potential

HCK HydroCracker

HDS HydroDeSulphurisation

HV High Voltage

ICE Internal Combustion Engine

IEA International Energy Authority

IEAGHG IEA Greenhouse Gas R&D Programme

IIASA International Institute for Applied Systems Analysis

IMO International Maritime Organization

ISE International Shipping Emissions

ISO International Organization for Standardization

ISOM Isomerisation Unit

IVL Swedish Environmental Research Institute

JRC Joint Research Centre of the European Commission

KHT Kerosene HydroTreater

LCA Life-Cycle Assessment (also Life-Cycle Analysis)

LCI Life-Cycle Inventory

LLV Legislated Limit Value

LV Low Voltage

LW Long Wave (radiation)

MAM Modal Aerosol Module

MARC The two-Moment, Multi-Modal, Mixing-state resolving Aerosol model for Research of Climate

MBS Mixtures of BC-Sulphate

MEA MonoEthanolAmine

MIT Massachusetts Institute of Technology

MOS Mixture of OC-Sulphate

NCAR National Center for Atmospheric Research

NEDC New European Driving Cycle

NHT Naphtha HydroTreating (unit)

NMC ***(also NCM)*** lithium Nickel Manganese Cobalt oxide

NO_2 Nitrogen Dioxide

NO_3 Nitrate Radical

Abbreviations and terms

(continued)

NO_x Nitrogen Oxides

NSU Naphtha Splitter Unit

NTNU Norwegian University of Science and Technology

OC Organic Carbon

OEM Original Equipment Manufacturer

OH Hydroxyl Radical

PM Particulate Matter

$PM_{2.5}$ Particulate Matter with an aerodynamic diameter less than 2.5 µm

POW Power/CHP plant

PTU Purge Treatment Unit

RDE Real-Driving Emissions

ReCAP Project initiated by IEAGHG to evaluate the cost of retrofitting CO_2 capture in existing oil refineries.

REFIT Regulatory Fitness and Performance Programme of the EU

RTS Reference Technology Scenario—IEA's base case climate scenario which takes into account existing energy and climate commitments, including those agreed at COP 21.

SDA Solvent DeAsphalting (unit)

SMR Steam Methane Reformer

SO_2 Sulphur Dioxide

SRU Sulphur Recovery Unit

SW Short Wave (radiation)

SW+LW Global Net Radiation

TOA Top Of the Atmosphere

TSAP Thematic Strategy on Air Pollution

TTW Tank To Wheels

UNFCCC United Nations Framework Convention on Climate Change

VBU VisBreaker Unit

VDU Vacuum Distillation Unit

VHT Vacuum gas oil HydroTreater

WEO World Energy Outlook

WLTP Worldwide harmonized Light vehicles Test Procedure

WPE Working Party on Environment (of the European Council)

WTT Well To Tank

WTW Well To Wheels

ZEV Zero-Emission Vehicle

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