How to decarbonise the French freight sector by 2050 ?

TRANSPORT & ENVIRONMENT

Transport & Environment

Publication date: May 2020
In-house analysis by Transport & Environment

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To cite this study

Transport & Environment (2020). How to decarbonise the French freight sector by 2050?

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Acknowledgements

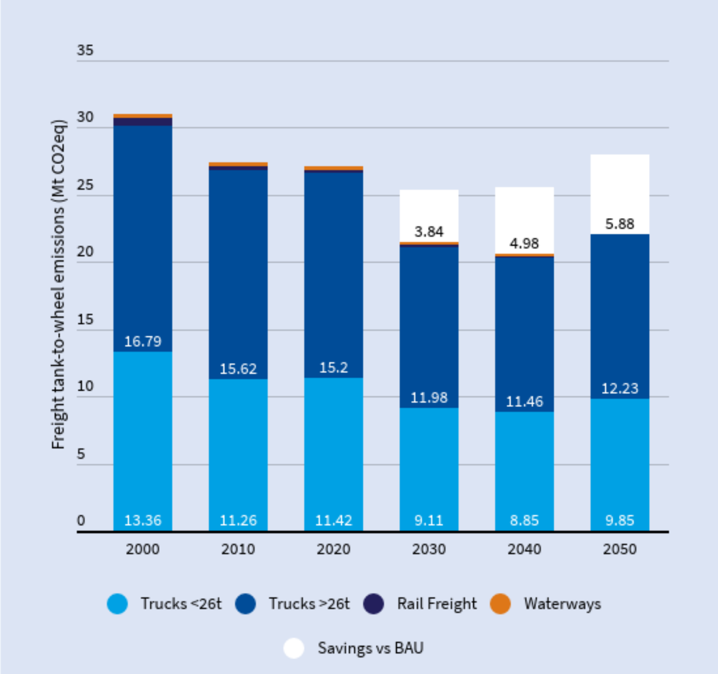
The authors kindly acknowledge the external peer reviews from Florian Hacker (Öko-Institut e. V.), Martin Koning (Ifsttar, Université Gustave Eiffel) and Urs Maier (Agora Verkehrswende). The findings and views put forward in this publication are the sole responsibility of the authors listed above. The same applies to any potential factual errors or methodological flaws.

Executive Summary

This study analyses measures and technologies which can contribute to the decarbonisation of the French inland freight sector. It comprises an emissions modelling exercise and a cost analysis for total cost of ownership (TCO) of long-haul trucks. It reaches the conclusion that, based on today's assumptions, battery electric vehicles (BEVs) in general, and those using an overhead catenary infrastructure (OC-BEVs) in particular, represent the most cost-effective pathways to achieve zero well-to-wheel inland freight Greenhouse gas (GHG) emissions in France by 2050.

Efficiency measures such as increased modal shift, improved fuel efficiency of trucks and optimised logistics efficiency can contribute to reducing freight emissions, but are not sufficient to reach the French 2030 targets under the *Stratégie Nationale Bas-Carbone* (SNBC) and *Effort Sharing Regulation* (ESR), let alone fully decarbonise the French inland freight sector until 2050.

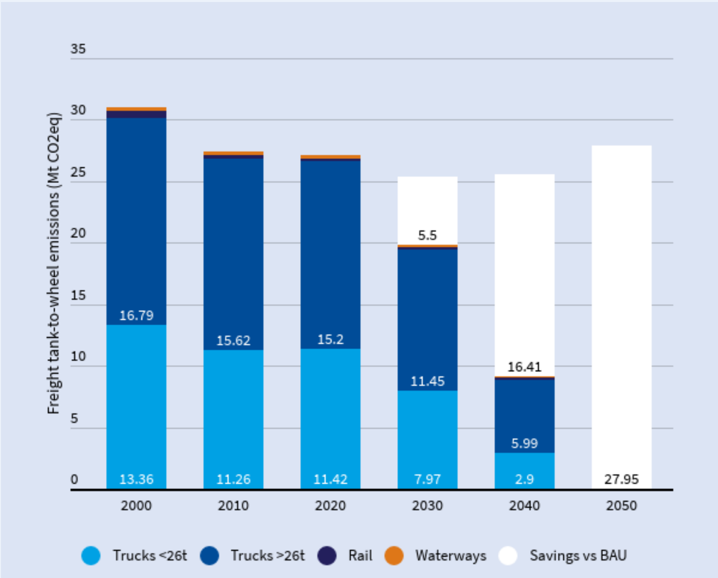
Combining all efficiency measures would result in a tank-to-wheel emission reduction of 18% by 2050 (compared to 2018). It will therefore be necessary to fully decarbonise the heavy-goods vehicle (HGV) fleet. This is technically possible but the transition needs to begin already in the early 2020s.



Business-as-usual vs. sum of efficiency measures

In addition to the efficiency measures, an ambitious uptake rate in zero-emission vehicle (ZEV) sales, a 2040 sales phase-out for trucks running on fossil diesel and a ban on the remaining fossil diesel fleet would lead to zero well-to-wheel emissions by 2050.

In 2030, new sales of HGVs will need to reach at least 30% (below 26 tonnes gross combined weight (GCW)) and 15% (above 26 tonnes GCW) ZEVs. The fossil diesel sales phase-out must happen no later than 2040. Even then, it would be necessary to impose a circulation ban on the legacy fossil diesel fleet in 2050 to reach the sector's full decarbonisation.



Efficiency measures, ZEV vehicle uptake, legacy fleet ban

Required uptake rate of new vehicle registrations for trucks below and above 26 tonnes GCW

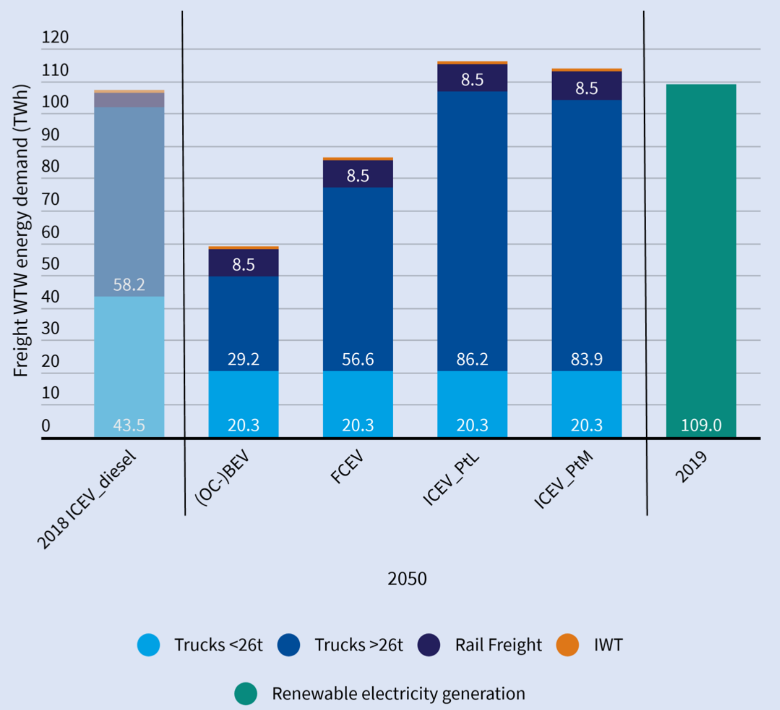
The drivetrain technologies, or *pathways to zero*, which can technically achieve this, include:

1. direct electrification through overhead catenary and battery electric vehicles, i.e. (OC-)BEVs
2. hydrogen-powered fuel cell electric vehicles, i.e. FCEVs, and
3. internal combustion vehicles fuelled by liquid or gaseous electrofuels, i.e. ICEVs_PtL or _PtM

All the pathways above rely on renewable electricity generated from additional production capacity and can be regarded as GHG-neutral from a well-to-wheel emissions perspective. They are subject to different conversion efficiency losses and therefore need varying amounts of renewable electricity.

In view of the techno-economic developments as well as market signals from truck manufacturers, it is reasonable to assume that, for the commercial vehicle segment with a GCW below 26 tonnes, battery electrification is proving to be the most cost-competitive pathway. The model therefore assumes that all trucks below 26 tonnes GCW will be BEVs across all pathways.

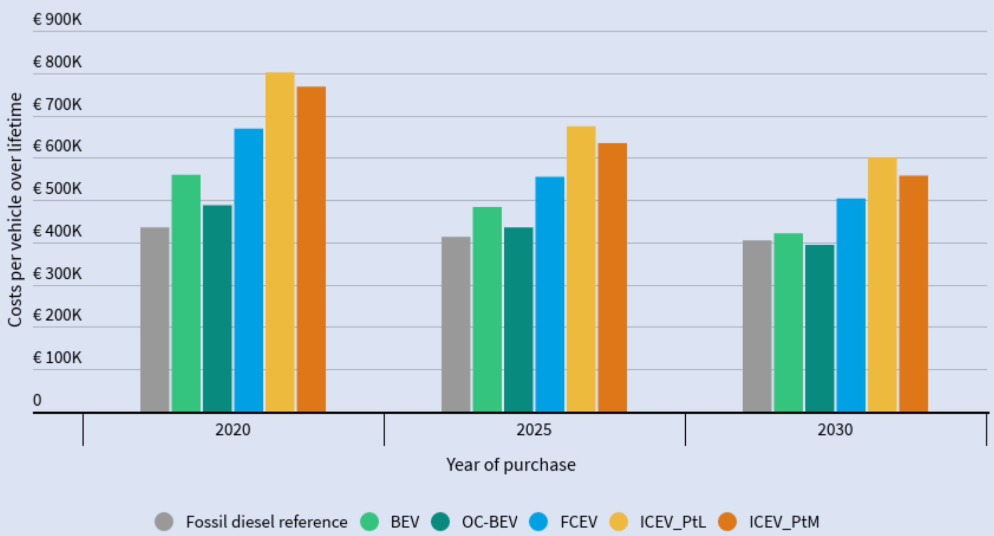
Direct electrification will, today and in the future, remain around twice as efficient as hydrogen, and around three times as efficient as internal combustion engines running on synthetic electrofuels. In 2050, the direct electrification pathway would require an equivalent of 54%, the hydrogen pathway of 79% and the two hydrocarbon pathways of 106% and 104% compared to the 2019 renewable electricity generation in France.



Additional electricity demand compared to 2019 renewable electricity generation in France

The costs due to renewable electricity are one of several cost components which need to be considered. When factoring in all vehicle purchase, operating and infrastructure costs as well as taxes, levies and road charges, BEVs and OC-BEVs have the lowest TCO when comparing all pathways. They will also remain cheaper to own and operate than FCEVs and ICEVs running on synthetic electrofuels when those electricity-based fuels are produced overseas and shipped to France (see section 5).

Total cost of ownership of long-haul trucks in France North Sea scenario



Notes: Nominal prices excl. VAT. Assuming a first use period of 5 years. Including total vehicle costs (retail price and residual value, maintenance & repairs, vehicle taxes, excl. financing costs), fuel costs (incl. grid connection fees, transport & distribution costs and taxes & levies), infrastructure costs (at full utilisation) and road charges.

Policy recommendations

A drivetrain transition towards direct electrification will be indispensable if France wants to meet its binding 2030 and 2050 climate targets at the least cost for the public sector, businesses and the consumer. Both French and EU policy measures adopted as of today will curb freight emissions but fall short of the magnitude which will be needed to reach the targets. The findings of this study should therefore prompt lawmakers in France to take swift and decisive regulatory action.

France is to develop a rail freight strategy before 2021. **We call on the French government to** simultaneously work on and **publish a road freight strategy** to set a credible pathway towards decarbonisation including intermediate emission reduction targets in line with the SNBC and the ESR and concrete policy measures to achieve this. As part of this, we call on the French government to implement the following policies to accelerate the switch to zero-emission road freight:

Taxation reform

There are currently no reduced tax rates foreseen for electricity used in road freight transport. A **reduced CSPE rate** is currently granted to the transportation of passengers by train, metro, tramway, electric bus and goods by train. This provision **should be extended to** the transportation of goods by road vehicles directly propelled by electricity, i.e. **BEVs and OC-BEVs**.

France is currently applying an **extremely low excise duty rate to fossil methane** as transport propellant. This lack of proper taxation cannot be justified when considering the negative climate and air quality impact. As a bare minimum, at least the full TICGN rate for fossil gas for household consumption should also be applied to fossil methane as a transport propellant.

The **diesel fuel rebate should be phased out as soon as possible**. The currently low oil prices are a good opportunity to make progress towards this goal. As this would disproportionately affect domestic hauliers more than their foreign competitors due to fuel tourism, a part of the additionally generated tax revenue could go to a new investment fund to provide purchase subsidies to small- and medium-sized haulier companies who wish to invest in zero-emission trucks.

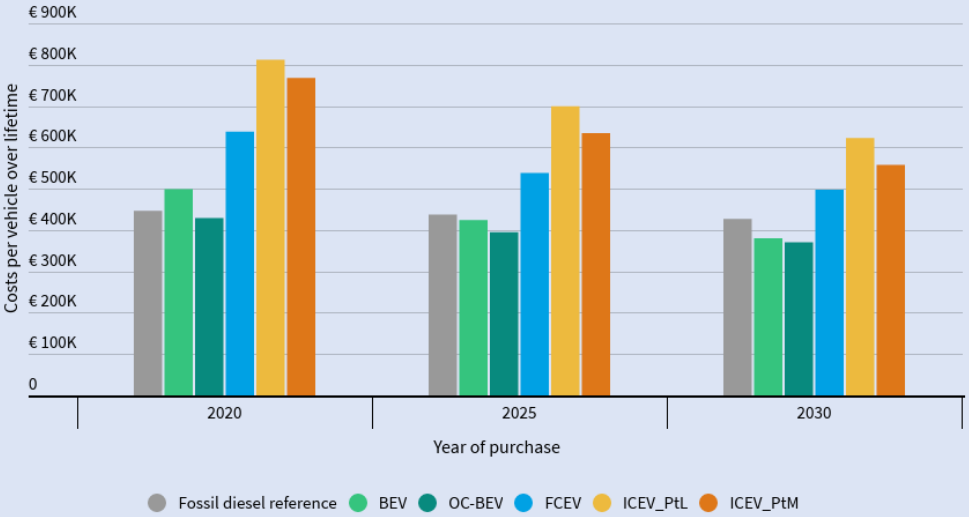
Purchase incentives for zero-emission vehicles

France should introduce a time-limited **direct purchase subsidy for battery electric- and hydrogen-powered trucks** as it was done by the German Federal Transport Ministry and in California. A French purchase subsidy should come with sufficiently high rates to maximise the steering effect. Any funding scheme should be limited to ZEVs and not apply to gas-powered trucks.

Taxation reform and purchase incentives: impact on the TCO

Combining the reduced CSPE tax rate for (OC-)BEVs, the fuel rebate phase-out after 2020 and an illustrative ZEV purchase subsidy based on the German scheme would reduce the TCO of ZEVs by up to 14%, while increasing the fossil diesel’s TCO by up to 5% (depending on the year). It would thereby bring forward price parity with fossil diesel to 2020 for OC-BEVs (from 2029) and to 2024 for BEVs (from 2039).

Total cost of ownership of long-haul trucks in France including tax reform and ZEV purchase subsidy - North Sea scenario



Notes: Nominal prices excl. VAT. Assuming a first use period of 5 years. Including total vehicle costs (retail price after residual value and purchase subsidy deduction, maintenance & repairs, vehicle taxes, excl. financing costs), fuel costs (incl. grid connection fees, transport & distribution costs as well as taxes & levies incl. reduced CSPE rate and fuel rebate phase-out after 2020), infrastructure costs (at full utilisation) and road charges.

Road charging

Currently, HGVs are not charged for the use of the publicly-managed road network. The French government should therefore **introduce a distance-based toll scheme** for all trucks with a GCW above 3.5 tonnes circulating **on publicly-managed roads**. It will need to comply with the rules of the currently ongoing revision of the Eurovignette Directive and include a meaningful reduction of the infrastructure charge for ZEVs. It should also introduce external cost charges for air and noise pollution.

Charging infrastructure

France should end the incentives and drop the targets included in its NECP for developing refuelling infrastructure for CNG and LNG vehicles, and shift its focus towards incentivising the infrastructure development for ZEVs. The French government should advance a formal strategy laying out its intentions how to support and ramp up the deployment of private and (semi) public charging infrastructure for urban-, regional delivery- and long-haul trucks. This includes the introduction of funding instruments which support transport companies and the logistics sector in installing private and shared infrastructure for depot and destination charging for urban and regional delivery trucks.

In terms of the deployment of hydrogen refuelling infrastructure for trucks, targets could be set for major European sea ports to leverage the synergy effects with the fuel's future role in maritime shipping and exploit its higher cost-effectiveness by saving on the significant distribution costs.

National sales phase-out of ICE trucks by 2035 and 2040

France should adopt a sales ban for ICEVs with a GCW below 26 tonnes for 2035 and above 26 tonnes for 2040. This would require the EU to adopt legislative measures allowing Member States to implement phase-outs in compliance with EU type-approval and internal market rules. The alternative would be to impose a ban on new registrations directly at EU level as part of the upcoming revision of the CO_2 standards for HDVs.

Zero-emission urban freight

Despite evidence that **gas-powered trucks do not offer meaningful air quality benefits** compared to diesel vehicles (see section 3.1.5), they are receiving the Crit'Air certificate 1, the least polluting category after ZEVs. This classification should be changed as soon as possible.

In this context, the development of a **zero-emission city logistics strategy** may be beneficial. The larger French cities should also consider introducing zero-emission zones for commercial vehicles (i.e. vans and trucks) with a view towards 2025 and including transitional arrangements for already registered vehicles until 2030.

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List of acronyms and abbreviations

BEV	Battery electric vehicle
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
CI	Compressed ignition
CNG	Compressed natural gas
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
DAC	(CO_2) Direct air-capture
ERS	Electric road system
ESR	Effort Sharing Regulation
EU ETS	European Union Emissions Trading System
EUTRM	European Union Transportation Roadmap Model
FCEV	Fuel cell electric vehicle
FT-synthesis	Fischer-Tropsch synthesis
gCO_2eq	Gram carbon dioxide equivalent
GCW	Gross combined weight
GDP	Gross domestic product
GHG	Greenhouse gas
HGV	Heavy-goods vehicle
HPDI	High pressure direct injection
ICEV	Internal combustion engine vehicle
ICEV_PtL	ICEVs using liquid electrofuels (synthetic diesel)
ICEV_PtM	ICEVs using gaseous electrofuels (synthetic methane)
ILUC	Indirect land use change
IWT	Inland waterway transport
LCOE	Levelised cost of electricity
LNG	Liquefied natural gas
NECP	National Energy and Climate Plan
OC-BEV	Overhead catenary battery electric vehicle
PI	Positive ignition
PtL	Power-to-liquid
PtM	Power-to-methane
PV	Photovoltaic power
SNBC	Stratégie Nationale Bas-Carbone (*National Low Carbon Strategy*)
TCO	Total cost of ownership
TEN-T	Trans-European Transport Network
TICPE	Taxe intérieure de consommation sur les produits énergétiques (*Domestic consumption tax on energy products*)
TICGN	Taxe Intérieure de Consommation sur le Gaz Naturel (*Domestic consumption tax on natural gas*)
tkm	Tonne-kilometres
TTW	Tank-to-wheel
TURPE	Tarif d'utilisation du réseau public d'électricité (*Transmission network access tariff*)
VECTO	Vehicle Energy Consumption Calculation Tool
vkm	Vehicle-kilometres
WTT	Well-to-tank
WTW	Well-to-wheel
ZLEV	Zero- and low-emission vehicle

1. Introduction

Transport is the biggest emitting sector in France with total annual emissions amounting to 134 megatonnes of CO_2 equivalent (Mt CO_2eq) and accounting for more than 30% of total greenhouse gas (GHG) emissions in 2017 - a share which stood at 22% in 1990.[1] Road transport represents more than 80% of all transport emissions, of which around 20% are due to heavy-goods vehicles (HGVs).[2]

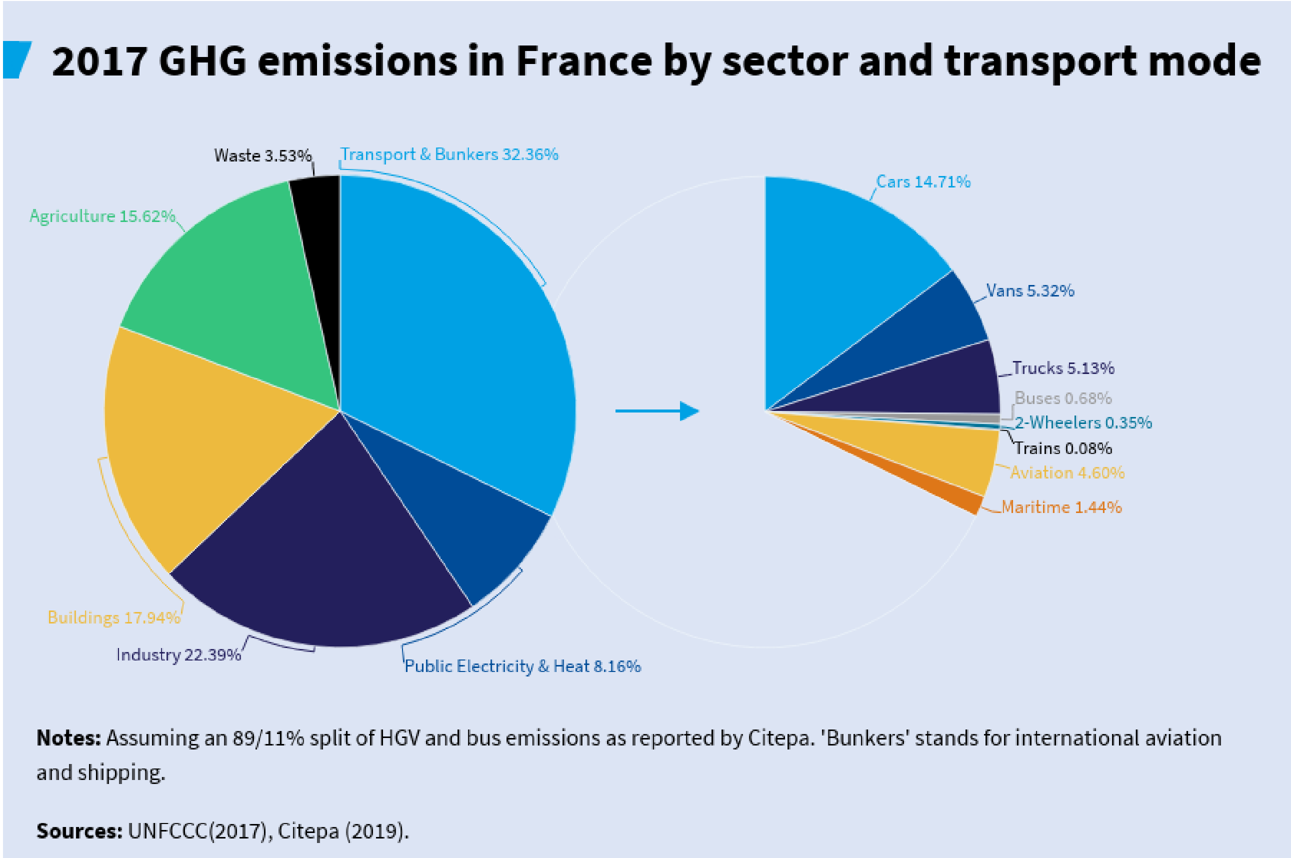

Figure 1: 2017 GHG emissions in France by sector and transport mode

Under the Effort Sharing Regulation (ESR), which sets national GHG reduction targets for those sectors not covered by the EU Emissions Trading System (EU ETS) and which includes the transport sector (except for aviation and international shipping), France is obliged to reach an overall GHG reduction of -37% by 2030 compared to 2005.[3,i] To achieve the ESR target, France's *Stratégie Nationale Bas-Carbone* (SNBC) sets a specific 2030 target of -32% for the French transport sector (compared to 2005).[4] The 2030 targets are expected to be further increased which would also have consequences for both the SNBC and ESR targets. Consequently, the French ESR target of -37% is taken as the benchmark for transport in this study. After the adoption of the climate neutrality target for 2050 (*Loi Énergie et Climat*)[5] and the inclusion of a specific target to decarbonise road transport by 2050 in the adopted mobility law (*Loi Mobilités*),[6] the country must now quickly reduce and bring the level of emissions from all transport modes to zero by mid-century. In concrete terms, this means that France must reduce road transport emissions from 125.6 Mt CO_2eq today to 84.2 Mt by 2030 and zero by 2050.[ii] Failing to substantially reduce inland freight emissions and eventually reach zero would make these French and European targets all but impossible to attain.[iii]

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[i] Excluding flexibility mechanisms.

[ii] Based on the national GHG inventory submissions to the UNFCCC and assuming an 89/11% split between HGVs and bus emissions as reported by Citepa.

[iii] It is assumed that the 2030 ESR target is equally applied across all road transport modes.

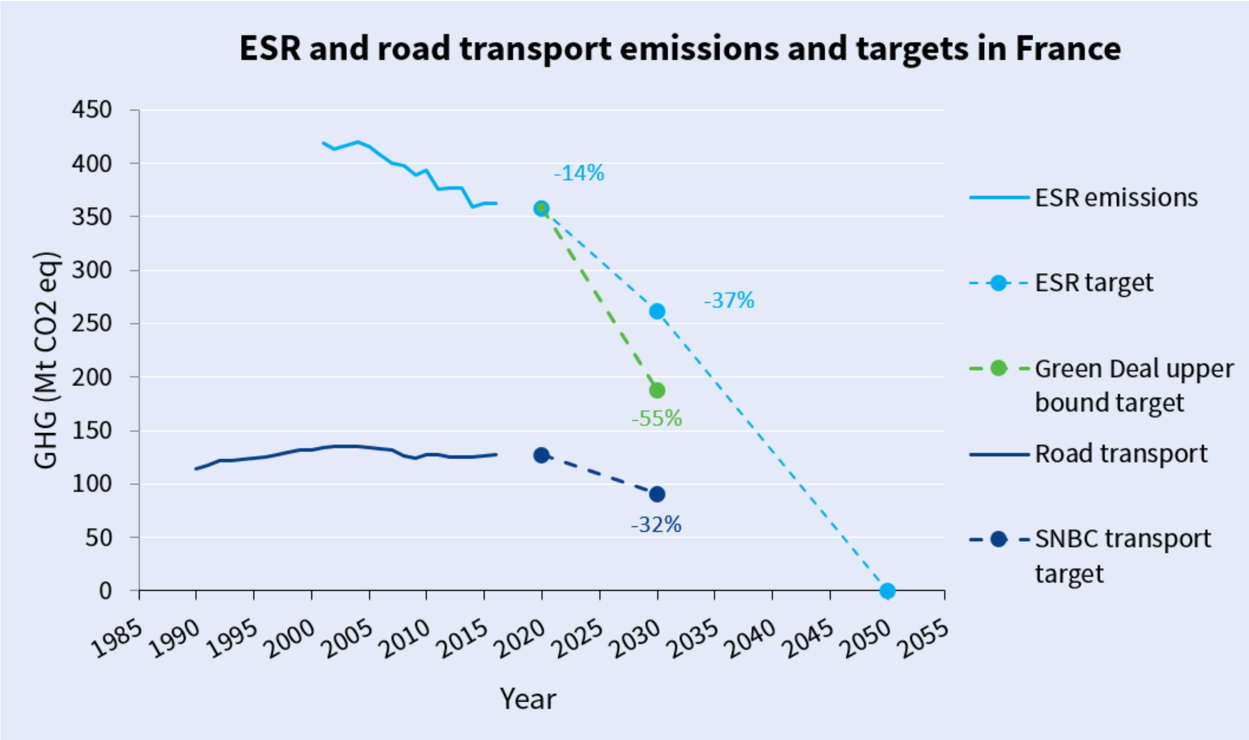


Figure 2: Emission trajectories and targets

Emissions from the inland freight sector and particularly from HGVs pose a major stumbling block to achieve these targets. In 2019, 336,000 rigid trucks and 211,000 tractors above 3.5 tonnes were registered in France.[7] More than 99% of these vehicles run on conventional fossil diesel.[8] These domestically registered vehicles account for 57% of the domestic road freight volume, while foreign registered vehicles make up the remaining.[9] This fleet, and additional vehicles due to the expected increase of future freight demand, will eventually need to be replaced with GHG-neutral alternatives.

The purpose of this study is to analyse instruments and technologies which can significantly contribute to completely decarbonise the French inland freight sector. The analysis is divided into the following sections:

1. Overview of the existing policy measures at both the French and the EU level
2. Methodology and definition of the business-as-usual scenario
3. Efficiency and other measures: overview and analysis of their potential to reduce emissions
4. Pathways to zero: overview of technologies which are capable to close the remaining gap and help France meet its binding 2030 and 2050 targets
5. Additional renewable electricity demand and cost analysis of the different technologies
6. Policy recommendations for France and the EU to decarbonise the sector

As this analysis will show, the so-called *efficiency and other measures* including modal shift, improved fuel efficiency and optimised logistics efficiency can contribute but will not be sufficient to reach full decarbonisation. There is a need to shift away from fossil fuels to GHG-neutral technology to decarbonise road freight. As long as there are HGVs circulating on French roads, they will need to run on clean electricity, whether directly or indirectly. The available technologies require different amounts of electricity and vary in their system and user costs. The options which are identified as capable to fully decarbonise road freight, the so-called *pathways to zero*, need to be based on renewable electricity generated from additional installed capacity, whether domestic or imported:

1. direct electrification in the form of battery electric and overhead catenary vehicles
2. hydrogen-powered fuel cell electric vehicles,

3. conventional internal combustion engine vehicles fuelled by synthetic diesel (PtL) or synthetic methane (PtM).

The options represent the techno-economic context for how France can achieve GHG emission reductions of -37% by 2030 and -100% by 2050.

1.1. Literature review

A number of recent studies have assessed the techno-economic aspects of freight decarbonisation in Europe in general, and in France in particular. While there has been some profound research on drivetrain technologies, their respective emission reduction potential and the system and user costs attributed to them, few of these publications have also taken into consideration the role of regulation which will be needed to drive the transition towards a zero-emission freight sector.

Transport & Environment laid out potential freight decarbonisation pathways for the EU and the Nordic countries in their 'roadmap to climate-friendly land freight and buses in Europe'.[10,11] Earl et al. published an 'analysis of long haul battery electric trucks in EU'.[12] Koning et al. published a socio-economic evaluation of 'how to reduce CO_2 emissions from freight transport in France'.[13] Cambridge Econometrics analysed the whole-economy impact in 'trucking into a greener future: the economic impact of decarbonizing goods vehicles in Europe'.[14] Schmidt et al. undertook a study on the 'future fuel for road freight'.[15] Mottschall et al. did a sensitivity cost analysis of different fuel options for long-haul transport in Germany.[16] Kühnel et al. carried out a techno-economic comparison of long-haul tractor drivetrains including the electrification based on an overhead catenary system and which also serves as the main source for the cost analysis in this study.[17] Briand et al. published an analysis on deep decarbonisation trajectories for freight transport in France.[18]

1.2. Adopted policy measures at national level

France has yet to introduce meaningful policies to decarbonise its inland freight transport sector. While the adopted mobility law includes a sales phase-out by 2040 for internal combustion engines (ICE) in the passenger and light commercial vehicle segment, there has been no such date announced for HGVs.[19] Regarding road haulage, the law does include a reduction of the diesel fuel rebate for HGVs (*remboursement partiel de la TICPE*) in the amount of € 0.02/litre,[20] slightly decreasing the rebate from the current average rate of € 0.177/litre.[21] The resulting additional annual tax revenue of € 140 million is earmarked for the *Agence de financement des infrastructures de transport de France* (AFITF).[22] The agency's 2020 budget for transport infrastructure investment has just been increased by € 500 million to a total of € 3 billion for 2020.[23] The French carbon tax (*Contribution Climat-Énergie*, CCE) will continue to be kept frozen at its 2018 level of € 44.6/tCO_2; the same applies to the diesel excise duty rate of € 0.59/litre (disregarding the rebate).[24]

The country's *National Climate and Energy Plan* (NECP) includes the objective to have 800 to 2,000 hydrogen-powered HGVs and 400 to 1,000 hydrogen refuelling stations. Also, some 330 to 840 refuelling stations for natural gas vehicles shall be established by 2028. The possibility of special depreciation for natural gas vehicle purchases shall be prolonged until the end of 2021 and extended to battery electric- and hydrogen-powered HGVs.[25] Critically, the legislative framework lacks concrete measures which would either considerably reduce freight emissions, strengthen the polluter pays principle or incentivise the uptake of zero-emission technology.

1.3. Adopted policy measures at EU level

In the recently concluded EU legislative period, lawmakers adopted the following legislative files which will help France reduce inland freight emissions:

CO_2 Emission Performance Standards for HDVs: the first fuel efficiency standards for new heavy-duty vehicles (HDVs) set fleet average reduction targets of 15% in 2025 and (at least) 30% in 2030.[iv] The uptake of zero- and low-emission vehicles (ZLEVs) is incentivised by a super-credits system capped at 3% by 2024, and a benchmark-based crediting system also capped at 3% from 2025 onwards. This means that, should manufacturers deploy a sufficient number of new ZLEVs, their fleet reduction target can be reduced by a maximum of 3 percentage points. There are four regulated categories of trucks covering 65 to 75% of HDV emissions.[26] The other categories (i.e. lighter trucks and buses) remain unregulated until 2022. The Regulation also includes a two-tonne additional maximum weight allowance for zero-emission vehicles (ZEVs).[27] However, this ZEV allowance is not directly applicable and Member States must transpose it into their national legal systems.

Weights and Dimensions Directive: The Directive grants derogations on the maximum vehicle length in order to make heavy-duty vehicles more fuel efficient and safer. After the adoption of a recent implementing act, it allows for new design measures to improve aerodynamics, vision, safety, and driver comfort. The new rules will enter directly into force in September 2020.[28]

Eurovignette Directive: Depending on the final outcome of the revision, infrastructure charges for HGVs will be varied according to their CO_2 tailpipe emissions and a mandatory reduction of 50 to 75% for ZEVs will be introduced.[29] Since existing concession contracts with French motorway operators will continue to be exempted from the new rules, the discount for ZEVs will have little impact on the country's privately-managed road network until the concessions are substantially amended or renewed.

Renewable Energy Directive (RED) II: The Directive sets a de facto advanced fuels target of 7% for 2030. Half of that will need to come from advanced biofuels (as per Annex IX of the Directive), whilst other advanced fuels (such as renewable electricity or synthetic electrofuels) can count for the remaining. It is difficult to estimate how much of these fuels would go to the road freight sector.

Both the French and EU policy measures discussed here represent the political context. They are the input to the business-as-usual (BAU) scenario which forms the baseline assumption of this study.

2. Methodology

The methodology comprises a mixed approach consisting of the emissions modelling and the cost analysis. The quantification of emissions is undertaken with the *European Union Transportation Roadmap Model* (EUTRM).[30] It is based on the ICCT's *Global Transportation Roadmap Model* (GTRM) and adapted accordingly to include the EU Member States plus the United Kingdom, Norway and Switzerland.

The EUTRM is a demand driven model that can compute GHG emissions in yearly intervals between 2015 and 2030, and 5-year intervals thereafter, up to 2050. Transport and freight demand are based on the gross domestic product (GDP) adjusted for purchasing power parity, which is determined by historical and projected GDP, population, and fuel costs for each country. All transport demand is then effectively met with unlimited transport capacity. The relationship between freight transport and GDP has been observed historically (see section 2.2) and this assumption is carried forward in time (freight transport demand shows a slight decoupling with GDP). Consequently, an increase of GDP will result in an increase of freight transport demand. In lieu of policy decisions, this new demand is then met by increasing the fleet size through additional new vehicle sales. In the model, freight transport demand does not differentiate for the type of transported goods nor for the transport distance travelled.

The EUTRM is initialised with historical data, whereby HGVs, the vehicle stock and number of new sales, mileage, fuel consumption, and load factor are considered. Fleet renewal and vehicle purchasing is based

[iv] The 2030 target will be reviewed in 2022.

on retirement curves and freight transport demand. In the business-as-usual (BAU) case and with the exception of already adopted policy measures, all of the aforementioned parameters are assumed constant for future years. The only projections made in the model are for GDP, population and freight transport demand. Quantifiable policy decisions will change mode-specific parameters. In the case of HGVs, these can include policy driven modal shift, fuel and logistics efficiency and drivetrain technology uptake. The strength of the EUTRM lies in its ability to combine multiple policy decisions, show their effect on the BAU case, and quantify the relative importance of policies in terms of their tank-to-wheel (TTW) GHG emission reduction potential.

Assumptions made under the untapped potential (UP) scenarios should not be understood as explicit policy positions but, instead, as hypothetical best-case estimates which may not materialise to the same degree in the future. The same reasoning applies to the selection of qualifying efficiency measures. In order to not underestimate the level of future final energy consumption of GHG-neutral vehicles and appropriately refer to the CO_2 fuel efficiency standards for trucks as they are currently legislated, a fleet-wide reduction of 30% was included in the sum of efficiency measures. It is important to keep in mind that the deployment of ZEVs will effectively lower the 2025 and 2030 targets, both through the crediting systems and because their counting as vehicles with zero tailpipe emissions will permit manufacturers to sell ICEVs with higher reference emissions than 15 and 30% below the baseline.

To reduce complexity, the combination of different technological pathways is neither considered in the emissions modelling nor the cost analysis. In the future, a mix of different drivetrain technologies may realistically happen to some extent. However, it should be noted that this may have negative implications for the utilisation rate and cost-effectiveness of charging and refuelling infrastructure as well as lower economies of scale for vehicle production and technology development.

2.1. Scope of the analysis

Road, rail and inland waterway freight are the three considered inland freight transport modes. The movement of goods is measured in tonne-kilometres (tkm) and the movement of vehicles in vehicle-kilometres (vkm). Road freight includes HGVs above a gross combined weight (GCW) of 3.5 tonnes. Other commercial vehicles, such as buses, vans and vocational vehicles, are excluded from the scope since they are difficult to compare in terms of their application purpose and techno-economic characteristics. Rail freight takes into account both electrified and diesel-powered freight movements. Inland waterway freight refers to freight transported by barges on navigable inland waterways. Due to their predominantly international nature, statistics on international air and seaborne freight pose conceptual difficulties when dealing with them in a manner consistent with inland freight modes and are therefore not included in this study. Transport & Environment has previously published detailed decarbonisation roadmaps for the European aviation and shipping sectors.[31,32]

The EUTRM only considers tank-to-wheel CO_2eq emissions. This means that upstream emissions during the production of fuels and electricity are not taken into account in the modelling. This is, however, not the case for the cost analysis. The starting point of all considered pathways is renewable electricity generated from additional production capacity, either offshore wind in the North Sea or solar photovoltaic (PV) power from North Africa. There is hence no risk of methodological distortion through potential differences in well-to-well emissions between the different drivetrain technologies.

Emissions in the EUTRM are based on the national GHG inventory submissions to the UNFCCC which are derived from national fuel sales and their allocation to different vehicle classes. Foreign registered trucks circulating on French territory often refill abroad and the resulting emissions are attributed to the respective Member State and not to France. For this reason, the modelling exercise comprises a calibration between today's final energy consumption and number of domestically registered HGVs which is then carried forward until 2050.

Lifecycle emissions from vehicle production and disposal are not taken into account either. It is expected that vehicle manufacturing emissions will decrease following the gradual decarbonisation of the power sector and manufacturing processes. The production of battery cells can generate considerable CO_2 emissions depending on the electricity used. The latest research evidence shows that today's carbon intensity of batteries is already much lower than previously estimated.[33] Recent announcements by manufacturers stress the fact that electric vehicle and battery cell production in Europe will cause near zero energy-related CO_2 emissions.[34,35] It is worth noting that HGVs usually run at maximum possible operation to reduce the total cost of ownership, with lifetime mileages reaching a million kilometres (or more) in the case of long-haul tractors. Consequently, the carbon intensity per transported tkm attributable to the production of the battery will be modest. The same is true for those emissions resulting from the deployment of refuelling and charging infrastructure. For example, Wietschel et al. found that the lifecycle emissions from the construction of an overhead catenary system are practically negligible compared to the well-to-wheel emissions during vehicle operation.[36]

Eventually, future well-to-wheel (WTW) and lifecycle emissions of GHG-neutral vehicles will depend on the carbon intensity of the electricity grid. The 2016 EU Reference Scenario forecasts that the already low carbon intensity of the French electricity production will decrease from 44 grams in 2019 to 21 gCO_2eq/kWh in 2050, following the gradual phase-out of the remaining installed fossil fuel generation capacity.[37,38] The country's electricity mix is currently dominated by nuclear power, which accounted for 71% of gross electricity generation in 2017.[39] The French government plans to reduce this share to 50% by 2035 with the decommissioning of the 14 oldest nuclear power plants and to replace the lost capacity exclusively with renewables.[40]

The system and user cost analysis of long-haul trucks looks into the costs due to vehicle and fuel production as well as refuelling and charging infrastructure deployment. System costs refer to the costs from manufacturing, assembling and selling the vehicle, producing, transporting and distributing the electricity and fuel and constructing and maintaining the infrastructure. Except for grid connection fees and the *Tarif d'utilisation du réseau public d'électricité* (TURPE), which represents the transmission network access tariff, the analysis excludes taxes, levies, road charges and subsidies. This has been a deliberate choice in order to better assess the economic costs for each technological pathway which need to be borne by the society (the manufacturer, the haulier, the consumer and the public sector). By contrast, the user costs, or total cost of ownership (TCO), take into account the current level of taxes and levies on vehicle ownership and fuels as well as road charges for the use of the road network in France.

A caveat regarding the sum of qualifying efficiency measures needs to be raised. The sum does not take into account possible interactions between modes due to changes in freight demand and transport costs, (i.e. *ceteris paribus*). This means that the potential emissions savings disregard that, for example, increased fuel efficiency would result in lower haulage costs and thus lead to higher road freight demand and a higher road modal share. For simplicity, any change in transport freight demand due to price elasticity from changing fuel costs is not fed back into the emissions modelling.

2.2. Defining the business-as-usual scenario

Assumptions made under the business-as-usual (BAU) scenario need to be viewed with caution, since they are subject to a range of uncertainty factors. Generally speaking, transport demand in terms of freight volume is linked to macroeconomic performance, industrial output and trade intensity, albeit this correlation varies among countries and it is unclear how it will develop in the future.[41] In France, freight transport intensity (i.e. freight transport volume relative to GDP) has been slightly decreasing over the past 15 years but the link remains fairly strong (see Figure 3).[42] The current level of freight transport intensity may not necessarily hold in the future (consumption behaviour may change, for example). It is assumed that freight transport intensity will slightly reduce further reaching an indexed value of 71 by 2050 for the sake of modelling transport demand herein.

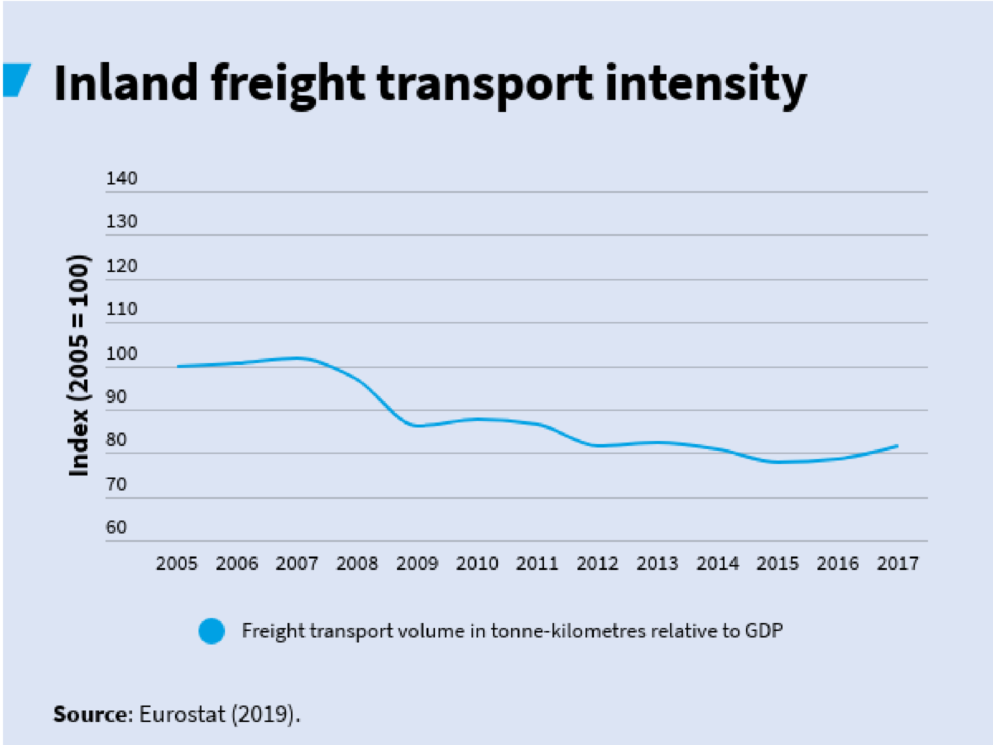


Figure 3: Inland freight transport intensity

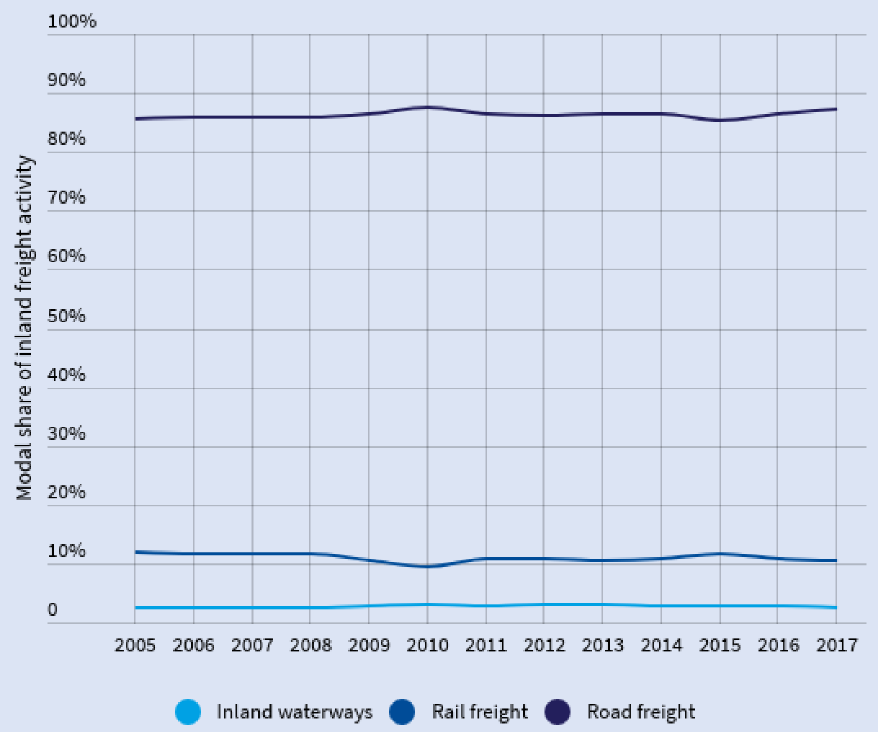
'France' always refers to Metropolitan France. Fuel prices are kept constant in the model but not in the cost analysis. In the EUTRM, GDP and population forecasts for France are based on projections from the 2016 EU Reference scenario, the OECD and the IMF. The projection of transport freight demand has been benchmarked against the *Scénario 1* presented by IDDRI.[43] The slight differences of around 10% are a result of projecting from a different historical baseline and the exclusion of vans. This also compares well to the 2050 demand projection of 420 billion tkm in the *Synthèse du scénario de référence de la stratégie française pour l'énergie et le climat* which also forms the basis for the SNBC.[44]

Measures to reduce freight demand by changing production and consumption patterns (like waste reduction, recycling, shorter transport distances) are not considered further in order to ensure a conservative estimate of future demand, but could indeed help make a contribution to the decarbonisation of the sector. Table 1 summarises the input data and the projection of freight transport demand driven by GDP and population growth.

Metric	2018	2030	2050
Population (million)	63.9	67.0	70.7
GDP (€2018 billion)	2,321	2,742	3,876
Freight transport demand (billion tkm)	320	354	454

Table 1: Socio-economic assumptions for the EUTRM

The relative modal share for rail and inland waterways has been declining over the past three decades, but has stabilised in the last ten years. It is assumed that the current share remains constant in forward projections in the BAU scenario. In terms of rail freight emissions, a linear decline of train-path-kilometres performed by diesel locomotives and their gradual replacement by battery electric and hydrogen trains is assumed until the mode reaches zero emissions in 2050. Similarly for inland waterway freight, it is assumed that the total vessel fleet will be directly electrified through batteries or indirectly using fuel cells and hydrogen by 2050.



Sources: European Commission (2017).

Figure 4: French inland freight modal split

The BAU scenario considers current trends and takes into account all national and EU measures adopted and implemented as of today. This includes all policies listed above under 1.1 and 1.2 in as far as they do constitute concrete regulatory instruments which are quantifiable in terms of emission reductions. Figure 5 shows the development of France's total tank-to-wheel freight emissions until 2050 under the BAU scenario. If no further action is taken, the inland freight sector will see its emissions marginally increase from 27.0 in 2018 to 28.0 Mt CO_2eq by mid-century. Freight transport demand will result in a 41% increase measured in tkm but final energy consumption will increase only 8% by 2050 compared to 2018. Without the adopted EU CO_2 standards, emissions would increase further because the French economy and, consequently, freight transport demand will continue to grow. Compared to the 2005 baseline of the ESR target, the BAU scenario results in a reduction of 21% by 2030. In 2050, emissions are 4% above those of 2018.

Figure 5: CO_2eq emissions of the French inland freight transport sector in the BAU scenario

3. Roadmap to zero-emission inland freight

This section sets out different measures to reach France's ESR target of -37% by 2030 and -100% for the road freight sector by 2050. Section 3.1 covers reduction methods using already existing or soon deployable technologies, the *efficiency and other measures*. Section 3.2 describes the different technological pathways which are capable of closing the remaining gap, the *pathways to zero*.

3.1. Efficiency and other measures

There is potential to reduce inland freight emissions by optimising existing technology, both through improving the efficiency of land freight vehicles and through increasing the efficiency of the transport system by utilising modal shift and optimising logistics efficiency. Efficiency and other measures are in this regard best understood as solutions which are based on conventional technology but whose real-world application would require increased investment in large-scale technological adoption and infrastructure development. In the following sections we present the main assumptions for each possible option under the business-as-usual (BAU) scenario and an untapped potential (UP) scenario. The emission reductions of the qualifying measures are subsequently added together to assess to what extent they can contribute towards France meeting its targets. The remaining gap is then addressed in the subsequent section laying out the pathways. The examined measures are:

1. increased fuel efficiency of trucks,
2. modal shift to electrified rail freight,
3. modal shift to inland waterway freight,
4. increased logistics efficiency,
5. fossil methane,
6. biomethane

3.1.1. Increased fuel efficiency of trucks

There are many different truck types and categories, ranging from urban to regional delivery to long-haul haulage. The fuel consumption of a given vehicle depends on multiple factors including the duty cycle, trailer attachment and respective payload. For the past 15 years, the uptake of fuel efficiency improvements for trucks has been rather limited.[45] Average fuel consumption of the average new tractor has been stagnating for more than a decade at around 33 litres/100 km.[46]

Improving the fuel efficiency of new trucks is considered to be one of the most effective ways to curb emissions. Fuel consumption can be reduced by optimising engine and trailer efficiency, reducing aerodynamic drag and deploying low resistance tyres. By applying all commercially available and prospective, but not yet widely commercialised technology that will be ready over the next 10 years, it would be possible to make trucks up to 43% more fuel efficient by 2030 (relative to a 2015 baseline), which translates to an annual reduction of around 3.6%.[47,48] This includes new engine technology with a peak brake thermal efficiency of 55% (today's reference vehicle is around 45%). Most, though not all, of these efficiency measures result in fuel savings that exceed their up-front capital and operating costs with payback periods of less than two years, and would therefore lead to net cost savings over the vehicle's lifetime for hauliers.[49]

Under the recently adopted EU Regulation, which is setting standards for tailpipe CO_2 emissions, truck manufacturers will be required to reach average fleet emission reductions of 15% by 2025 and at least 30% by 2030 (compared to the baseline year 2019 - 2020).[50] The CO_2 standards cover certain categories of rigid and tractor vehicles, which account for 77% of new vehicle registrations and 65 to 75% of CO_2 emissions from HDVs.[51,52] The fleet-wide targets can be lowered further by a maximum of 3 percentage points through the so-called zero- and low-emission (ZLEV) factor if truck makers deploy a sufficient number of ZLEVs.[v] ZEVs are counted as vehicles with zero tailpipe emissions. Therefore, the higher the number of ZEVs manufacturers will deploy, the more ICEVs with higher reference emissions than 15 and 30% below the baseline they can sell. The CO_2 reference values are calculated on the basis of the VECTO simulation tool.

BAU scenario: The model assumes increased fuel efficiency in accordance with the adopted CO_2 standards, while disregarding that the deployment of ZLEVs will slightly lower the fleet reduction target for 2030. Currently unregulated vehicle sub-groups continue to be excluded. After 2030, no successor standards are adopted and no further fuel efficiency improvements are assumed.

UP scenario: To fully unleash total fuel efficiency potential and go beyond the 2030 CO_2 standards, the technologies would need to reach cost-competitiveness. For that to happen, the technology must be readily available and its market uptake scaled up. Also, road haulage would need to account for a larger share of its caused externalities than it does today. With the right price signal and more stringent emission standards, a -43% reduced fuel consumption could be achieved across all vehicle sub-groups including the currently unregulated ones. This is likely the maximum technical potential from improving thermal engine efficiency, aerodynamics and rolling resistance and also includes hybridisation. Beyond 2030, no further improvement is expected.

[v] Authors' calculations.

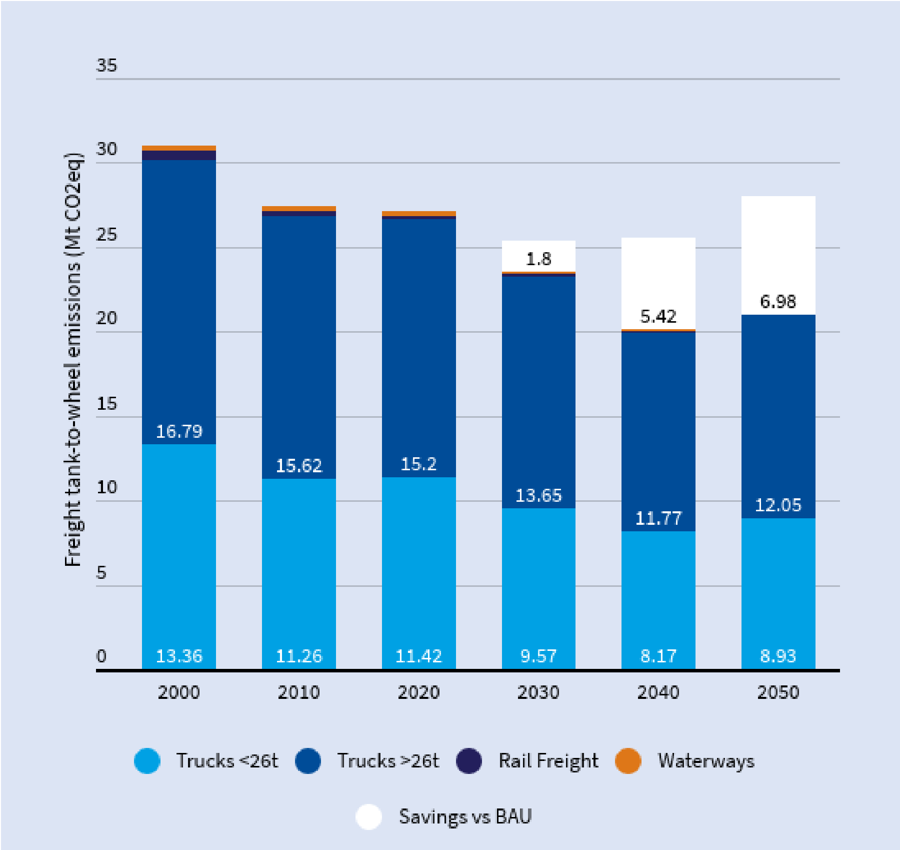


Figure 6: Infographic BAU vs. UP increased fuel efficiency

The results of increased fuel efficiency by 43% are shown in Figure 6. It would lead to a 22% reduction in CO_2eq freight emissions by 2050 compared to 2018, or a 25% reduction compared to BAU emissions in 2050.

3.1.2. Shift to electrified rail freight

Rail currently accounts for 10.5% of the modal split based on tkm.[53] The amount of transported goods by rail in France decreased from 57.7 in 2000 to 33.4 billion tkm in 2017, a volume reduction of 42% since the turn of the century.[54] Rail freight is significantly more energy efficient than road haulage due to its high rate of electrification. 67% of the French railway network length, which is suited for freight movements, is already electrified.[55] In 2016, 65% of train-path-kilometres and 76% of tkm were performed on electric traction.[56] Data from *SNCF Réseau* shows that around 80% of daily operated diesel train-path-kilometres are running on railway tracks which are already equipped with electric overhead lines.[57] This is often unavoidable as a result of the non-electrified last mile of rail freight movements.

Due to the fact that freight diesel locomotives reach a life span of 30 years and more, the decommissioning of the rolling diesel stock would take decades without an accelerated phase-out.[58] Gradually replacing the diesel rolling stock in the course of their decommissioning will reduce the already low carbon intensity of rail freight. In the case of the 33% of non-electrified tracks which are suitable for freight movements, battery electric- and hydrogen-powered locomotives can offer a cheaper solution compared to the construction of overhead lines where service frequencies are too low to reach cost-effectiveness.[59]

Multiple reasons help explain the low rail freight modal share. For distances of up to 500 km, moving goods by road is often superior to rail in terms of cost, time, flexibility and adaptability.[60] Likewise, rail freight is highly dependent on the type of goods being transported and more suitable for bulk commodities.[61] Road haulage is the preferred mode for unit load freight and faces also practically no cross-border barriers. Rail track access often needs to be granted up to a year in advance or on a rigid ad-hoc basis due to network planning requirements, which makes it inflexible for just-in-time production and fluctuating demand from shippers.[62]

BAU scenario: The completion of the Trans-European Transport Network (TEN-T) will improve the attractiveness of international rail freight services and increase cross-border interoperability.[vi] No other additional national measures are taken to boost rail. The model therefore assumes a linear decline of train-path-kilometres performed by diesel locomotives until they reach zero by 2050. Rail freight will also need to make up for a declining bulk cargo market of fossil fuels and refined petroleum products, although these goods already make up less than 10% of driven tkm in France today. A substantial shift from road to rail does not take place and it is therefore assumed that rail will maintain its current modal share of 10.5% in France, which nonetheless will lead to an increase of capacity to 48.8 billion tkm, given increased freight demand.

UP scenario: Growth potential will only be fully utilised if the infrastructure is improved and rail shipping is made more reliable and flexible (e.g. by automating and digitising the rolling stock, increasing average train speed as well as length and promoting combined and intermodal transport including 'rolling motorways').[63] Road haulage costs will also need to increase to better account for externalities and make rail more cost-competitive.[64] The literature projects that a considerable shift to rail is indeed possible if strategic investments and inter- and multimodality are prioritised. Briand et al. consider an increased modal share of 13% for rail freight by 2050 as achievable.[65] The French government projects that a rail freight modal share of 12% by 2050 is possible.[66] This is roughly equivalent to the BAU projected activity. The UP scenario assumes that rail freight capacity can be increased to 63.5 billion tkm by 2050, resulting in a modal share of 14%. This potential is equivalent to increasing today's capacity by around 84%. This shift comes only from HGVs above 26 t because they perform the longest distances. This exceeds the 2000 peak rail activity in France, which reached 57.7 billion tkm, although in 2050 there will be less bulk goods (e.g. due to the phase-out of coal and petroleum products) being transported by rail compared to 20 years ago. In short, this represents a highly ambitious scenario for shifting road freight to rail.

3.1.3. Shift to inland waterway freight

Inland waterway transport (IWT) currently accounts for 2.4% of the modal split based on tkm in France.[67] The amount of transported goods decreased from 9.20 in 2007 to 7.26 billion tkm in 2018, a volume reduction of 21% over the last decade.[68] France has an extensive network of navigable inland waterways totalling 8,500 km.[69] Around 75% of this network, however, consists of shallower rivers and canals which can only accommodate barges carrying lighter loads, thus eliminating the mode's scale advantages in terms of freight volume.[70] According to Eurostat, France has 5,060 km of waterways in use.[71]

Like rail, inland waterway transport offers the opportunity to shift freight volume away from the road. IWT is not only less carbon intensive but can bring about reduced air pollution, increased safety and potential cost savings. Yet, it suffers from similar structural disadvantages in terms of cost, time, flexibility and adaptability as is the case for rail freight. For waterborne transport to be time-effective and economically viable, significant and continuous infrastructure investment in the network is required. Already existing waterways need to be repeatedly dredged and waterway infrastructure facilities operated and maintained.[72] IWT is also largely confined to the transport of bulk commodities and, to a lesser extent, standardised container transport. And finally, it is subject to even stronger geographical limitations than it is the case for rail freight.

The technology for zero-emission shipping has been put into practice today in Norway and Denmark and concept barges have been developed in the Netherlands.[73,74,75] Stringent operational CO_2 and zero-emission port standards will be required to drive this technology change.

[vi] The TEN-T network, together with the integrated Rail Freight Corridors (RFC), aims to remove cross-border bottlenecks and facilitate easier long-distance transport in Europe.

BAU scenario: France has the obligation to complete the TEN-T core network by 2030 and the comprehensive network by 2050.[76] This includes the inland waterway *Seine–Scheldt* cross-border project on the North Sea whose completion is scheduled for 2030.[77] Country-to-country flows between France and its neighbouring countries Belgium and the Netherlands are among the highest for intra EU-28 road freight transport.[78] The European Commission estimates that opening this bottleneck could help cater for up to 15 million tonnes of freight annually and reduce transport costs.[79] Apart from this, no additional national measures to boost waterway freight are announced. The bulk freight volume of fossil fuels and refined petroleum products accounted for 10.4% of total IWT tkm in 2018, down from 18.8% in 2007. Around 50% of this drop can be explained by the decline in fossil fuel and petroleum products.[80] In the long term, the remaining fossil fuel volume will eventually disappear altogether and will need to be compensated for by other cargo demand. The model assumes that the Seine-Scheldt project will make up for this decline and enable enough growth to maintain IWT's current modal share until 2050. All vessels are assumed to reach zero emissions by 2050.

UP scenario: Similar to rail, growth potential of IWT will only be fully utilised if the infrastructure is systematically extended and its quality improved. Road haulage costs will also need to increase to better account for externalities and to make IWT more cost-competitive. For this study, we assumed that the current capacity for IWT in France could be increased to 15 billion tkm, resulting in a modal share of 3.3% by 2050 in the UP scenario.[vii] This shift comes only from HGVs above 26 t because they perform the longest distances. As it is the case for rail, this signifies a considerable increase (+100%) of absolute freight volume transported by inland waterways compared to today.

[vii] From 1990, Belgium doubled its inland waterway capacity without extending the network, while Romania increased capacity by a factor of six, also without extending the network. In terms of the available length of the waterways and activity on it, France has a low utilisation (1.5 million tkm freight/km waterway) compared to Belgium (7.3 million tkm/km), Germany (7.2 million tkm/km), the Netherlands (7.8 million tkm/km), and Austria (5.8 million tkm/km). Considering the lack of studies on the maximum potential of inland waterway freight transport in France, a doubling of the capacity is deemed achievable.

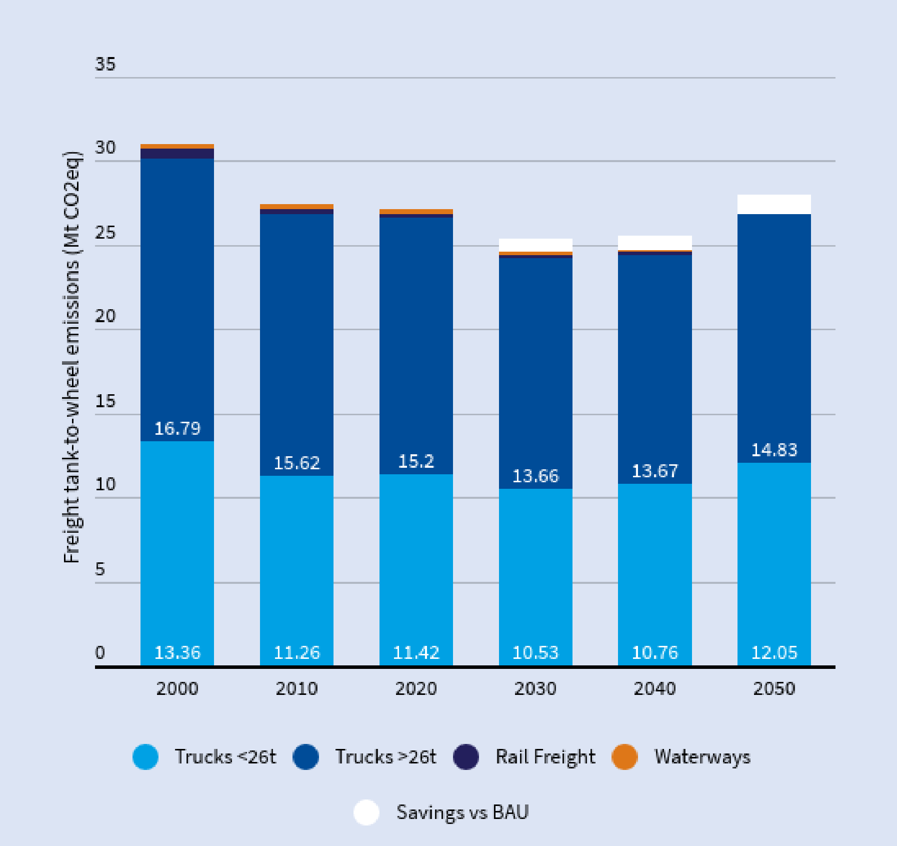


Figure 7: Infographic BAU vs. UP shift to rail and IWT

The results of ambitious modal shift to both rail and inland waterways are shown in Figure 7. The change in emission reductions, however, is rather marginal, with 2050 emissions projected to be equivalent to 2018 emissions, or a 4% saving compared to the BAU scenario in 2050.

3.1.4. Increased logistics efficiency

Freight transport demand and, consequently, final energy consumption and emissions can be reduced by optimising freight logistics efficiency and better utilising the existing vehicle capacity. The share of empty headings has decreased in France from 25% in 1999 to 18% in 2017. Yet, still close to a fifth of vkm on French territory are performed empty.[81] Despite the lack of concrete statistical evidence, it is probable that a further share of vkm are performed by only partially loaded vehicles.[82]

In some cases, empty and underutilised runs cannot be avoided due to technical or operational reasons.[83] Regional trade imbalances and port traffic as well as practical limitations to consolidate consignments will always result in some level of suboptimal utilisation of freight capacity. This is even more the case since today's widespread just-in-time manufacturing favours smaller transport units and requires carriers to respond with flexibility to short-term needs of shippers. It is expected that the current trend towards even more complex supply chains and a greater transport intensity as a result of the internationalisation of production processes will continue in the coming decades.[84] Nonetheless, there is still great potential to reduce freight volume through, for example, cargo consolidation, cube optimisation and floor loading.[85]

One key reason why hauliers can afford empty and partially loaded trucks is the currently low cost level of road haulage. The level is so low because the road haulage sector only partially pays for their external costs through taxes and excise duties.[viii] Charges would need to increase significantly in order to meet the polluter-pays principle and cover the externalities which are caused by inland freight to a greater extent

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[viii] The plan to introduce road charges for goods vehicles above 3.5 t on the publicly-managed road network, the so-called *ecotaxe*, was dropped eventually in 2014.

than it is the case today.[ix] In regards to France, HGVs cause € 3.70, rail € 1.50 and inland waterways € 2.11 of external costs per 100 tkm, whereby more than 90% of the resulting absolute freight-related costs are due to HGVs.[86,x] Besides, HGVs with a GCW of 7.5 t and more receive a fuel rebate when refuelling in France.[87] The rebate amounts to an average deduction of around € 0.177/litre, which reduces the diesel excise duty rate by a third (disregarding VAT).[88,89,xi] Removing, or at least significantly reducing it would create a strong incentive for operators to better utilise loading capacity, consolidate consignments and shift freight volume to rail and inland waterways. Cost incentives will also make it more profitable to invest in the digitalisation of supply chain processes, facilitate the real-time management of traffic and cargo flows, encourage the pooling and sharing of loading capacity and improve inter- and multimodality.

BAU scenario: Apart from the reduction of the fuel rebate by € 0.02/litre included in the 2020 budget law,[90] no substantial increase of taxes, excise duties or road charges for HGVs is planned in France. Road haulage continues to be kept at a low level and no further incentives are provided to address the underutilisation of vehicles. Supply chains and distribution networks will be, to a limited extent, further optimised which is assumed to lead to a negligible freight transport demand reduction.

UP scenario: To align the current artificially low cost level with the external costs caused by road haulage, vehicle taxes, fuel excise duties and road charges in road transport need to rise. In 2018, the French treasury received around € 4.3 billion in fuel taxes from HGVs (after the rebate).[xii] This public revenue will likely diminish in the future as a result of declining fuel consumption.[91] One idea to compensate for this would be to increase toll charges, differentiate them based on environmental performance and extend their coverage to the total road network. With road freight better reflecting its real costs and optimised logistics processes, it is assumed that the amount of vkm performed by empty vehicles could be reduced by a quarter and freight transport demand reduced by a total of 5% starting from 2030.

[ix] The level of required increases depends on which external costs are considered as internalised today. Except for the carbon tax rate of € 44.6/tCO_2 which is included in the diesel excise duty rate, HGVs on the privately- or publicly-managed French road network are currently not explicitly charged for their externalities. The fuel excise duty and road tolls can be viewed as implicit charges.

[x] It is worth noting that the mode-specific rates also include costs incurred from accidents, congestion and habitat damage, which usually make up around half of total external costs. These partial costs would also be caused by ZEVs in the future. Other cost factors include air pollution, climate (well-to-tank and tank-to-wheel) as well as noise.

[xi] The mentioned fuel rebate is the 2019 weighted average rate for France; the exact rates vary between regions. The paid out refunds amount to an estimated annual tax revenue loss of at least € 1.2 billion based on government revenue statements.

[xii] Authors' calculations.

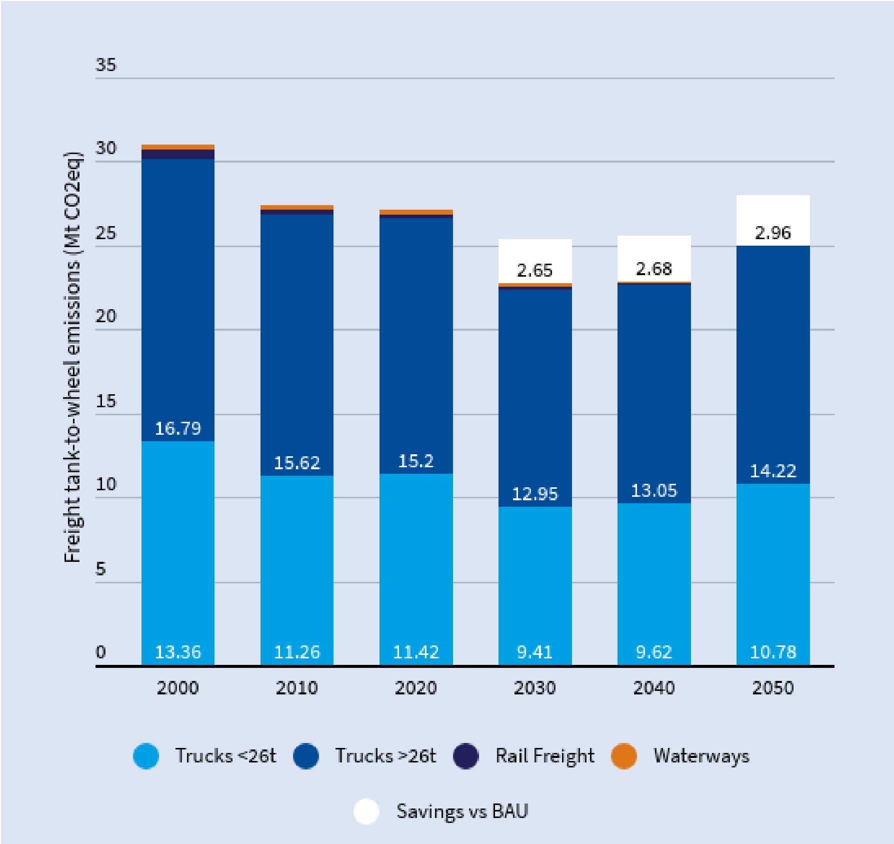


Figure 8: Infographic BAU vs. UP increased logistics efficiency

The results are shown in Figure 8. Increased logistics efficiency leads to a 7% reduction in emissions by 2050 compared to 2018 emissions, or an 11% saving compared to the BAU scenario in 2050.

3.1.5. Fossil methane

Some industry stakeholders and truck manufacturers see fossil methane as a promising pathway to reduce emissions of HGVs. Methane (CH_4) is the main component of natural gas which is hereafter called fossil methane (or fossil gas) in order to differentiate between the different production pathways for fossil-, bio- and power-to-methane. The gaseous fuel can either be compressed or liquefied for storage purposes and combusted in a modified thermal engine to propel the vehicle.

Transport & Environment has previously argued against the use of fossil methane in the heavy-duty sector for multiple reasons: Fossil methane offers only a limited GHG reduction potential on a WTW basis for a variety of reasons which include methane leakage, engine slip and boil-off emissions. In addition, trucks powered by LNG offer no meaningful air pollutant reductions in terms of nitrogen oxide (NOx) and particulate number (PN) emissions under real-world driving conditions, and may perform even worse than the best-performing diesel vehicles under certain driving cycles, particularly during urban driving.[92,93]

Gas vehicles can be equipped with a stoichiometric positive-ignition (PI) or a dual-fuel compressed ignition (CI) engine in combination with high pressure direct injection (HPDI) technology. The dual-fuel engine is primarily powered by methane and uses diesel as secondary fuel to ignite the fuel-air mix.[94] Compared to diesel, opting for gas as fuel translates into an additional fuel consumption of around 10% (CI engine) or 15-20% (PI engine), whereas the use of HPDI technology can eliminate these efficiency losses.[95,96,97] The fuel can either be compressed at 200 bar (compressed natural gas, CNG) or cooled down until it liquefies at -161°C (cryogenic liquefied natural gas, LNG) to increase volumetric density.[98,99] Storing methane in the form of LNG leads to a higher energy consumption due to the liquefaction and distribution which increases the fuel's production costs.[100,101]

The technical specifications of gas vehicles in the HGV class do not differ, no matter whether the used fuel is derived from fossil-, bio- or power-to-methane production paths, provided that the methane is purified and upgraded for the use as transport propellant. This effectively means that the automotive fuel and combustion characteristics are de facto identical.[102,103]

In terms of fossil methane's emission reduction potential, vehicle manufacturers claim CO_2 savings of 10 and up to 20% on a tank-to-wheel basis compared to diesel.[104,105,106] Tests commissioned by the Dutch Government and conducted by the research organisation TNO have shown that tank-to-wheel real-world driving emissions of LNG-powered trucks are between 3% to 10% (PI engines), and 14 to 19% (CI engines with HPDI) lower, depending on the reference diesel vehicle.[107,108,xiii] Despite this, increased GHG emissions due to methane leakage and boil-off from the gas supply chain nullify such savings according to recent research findings.[109,110] When factoring in all lifecycle emissions of LNG, including those emitted during extraction, processing, liquefaction, transport and distribution, the total savings become negligible in the case of CI engines with HPDI, or can even become negative in the case of PI engines.[111] This is because well-to-tank emission factors associated with imported LNG can be around 35% higher than those associated with fossil diesel, primarily due to extracting and liquefying the gas.[112] In the EU, average emissions for the well-to-wheel LNG pathway can be around 26% higher compared to fossil diesel.[113,xiv]

In regards to fuel costs, fossil methane is often considered to be an affordable transport fuel. This is mostly due to the preferential tax treatment which France is granting to fossil gas used as a transport propellant.[114] If methane was taxed based on the diesel tax rate and after deducting the diesel fuel rebate, today's natural gas retail price in France would not be € 1.04/kg_{LNG} but instead increase to €1.57/kg_{LNG} (accounting for the differences in energy density and disregarding VAT).[xv,115,116] Given that total GHGs from fossil gas are not appreciably lower than those of diesel, there is no conceivable justification for the current tax break methane is benefitting from in France.

On the basis of the preceding reasoning, fossil methane fails to qualify as a suitable measure due to the negligible well-to-wheel emission reduction potential. It is therefore not further considered in this study.

[xiii] TNO also included emissions incurred from tailpipe methane slip, tailpipe N_2O emissions, fuel tank boil-off gas, crankcase venting, leakage and blow-off in their tank-to-wheel calculation.

[xiv] Both well-to-tank and well-to-wheel GHG emission factors measured in gCO_2eq/MJ-fuel supplied.

[xv] There is no established market price for LNG yet. Refuelling stations in France either do not communicate prices publicly or charge a politically motivated price. Disregarding the additional costs due to liquefaction, storage and distribution, the authors therefore assume an LNG retail price in line with the CNG retail price of € 1.25/kg_{CNG}. The *Taxe intérieure de consommation sur le gaz naturel* (TICGN) for natural gas as propellant is €-cent 5.80/kg (€ 5.23/MWh), whereby 20% VAT is applied on the already charged price. The French TICPE for diesel as propellant is €-cent 59.40/litre (€ 41.7/litre after deducting the average fuel rebate).

	High-GHG	GHG-neutral
Fossil gas	**Natural gas** produced from both conventional and unconventional sources **Hydrogen** produced from natural gas via steam-methane reformation without CCS **Hydrogen** or **power-to-methane** produced from electricity bearing upstream emissions without CCS	**Hydrogen** produced from natural gas in a process that captures all supply chain GHGs and process CO_2 through CCS
Renewable gas	**Biomethane** produced from purpose grown-crops with high direct or indirect land-use change (ILUC) emissions	**Hydrogen** or **power-to-methane** produced from additional renewable electricity with zero GHGs and CO_2 from direct air-capture (DAC) **Biomethane** produced from sustainable and advanced feedstocks whose avoided methane emissions offset or exceed production and combustion GHGs

Table 2: Gaseous fuels and their definitions. Based on Searle et al. (2017)[117]

3.1.6. Biomethane

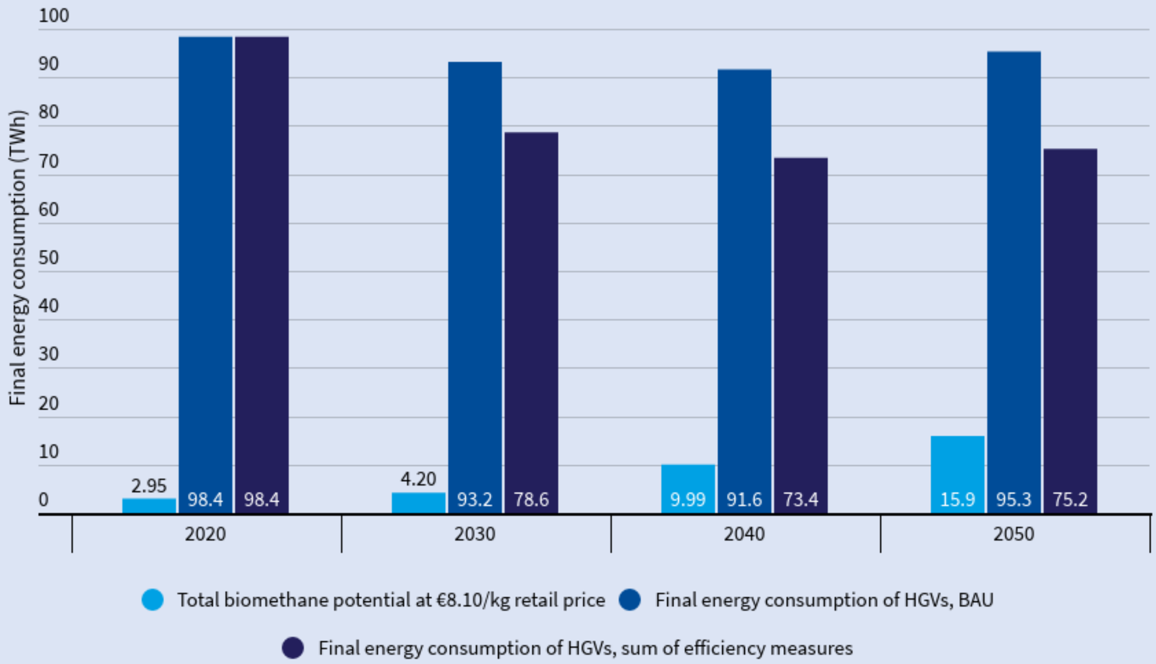
Similarly to fossil methane, biomethane is often viewed as a way forward to reduce GHG emissions from HGVs. This subchapter examines the increased use of biomethane as an efficiency measure and not as a potential standalone pathway because its sustainable production potential is too limited. The reasons for this are the constrained availability of sustainable feedstock and the non-competitive cost level without significant policy support compared to alternatives (including fossil diesel and fossil methane).

The technicalities of ICEVs using methane as a transport propellant, which are discussed in section 3.1.5. on fossil methane, apply in the same manner to biomethane (engine efficiency, fuel storage, air pollutant emissions and necessary engine adaptations).

Whereas first-generation crop-based feedstocks should not be considered due to their high emissions from direct and indirect land use changes (ILUC) and negative environmental impacts, advanced waste- and residue-based biomethane produced from anaerobic digestion and gasification of biomass can indeed deliver strong GHG reductions if certain sustainability safeguards are applied (see Table 2). The issue, however, lies with the high production costs and the constrained production volume due to limited feedstock availability.

France's national primary energy consumption of fossil gas was 426.8 TWh in 2018.[118] According to *Gaz Réseau Distribution France* (GRDF), 122 biomethane production sites injected around 2.1 TWh into the French gas grid in 2019, with an additional 1,000 plants and 21.4 TWh being foreseen in the capacity register.[119] The French government aims for 24 to 32 TWh of biomethane production in 2028 according to its *Programmation pluriannuelle de l'énergie* (PPE), of which between 14 and 22 TWh shall be injected into the grid.[120] Taking the mid-point here, 28 TWh of total biomethane production could cover less than 7% of the government's total primary gas consumption projection for 2028 (420 TWh).[121] A significant share of the 2018 biomethane injection volume is already coming from waste and residue feedstocks.[122] The potential to increase this in a sustainable manner should therefore be regarded as rather limited.

Searle et al. estimated the maximum sustainable biomethane potential at different cost levels in France and concluded that, in contrast to the French government target, a far lower production level would be capable of meeting the necessary sustainability criteria.[123] Taking into account total lifecycle GHG emissions, they considered livestock manure, sewage sludge, gasified biowaste and crop residues as feedstocks having no or, in part, negative GHG emissions. According to their analysis, France could supply a total of 2.9 TWh of sustainable biomethane in 2020 at a retail price of € 8.10/kg_{CNG}, which is more than six times the level of the current fossil CNG retail price. Under the same cost level, they estimated a production potential of 4.2 TWh for 2030 and 15.9 TWh for 2050.[xvi] For comparison, the final energy consumption required by an HGV fleet running increasingly on methane would amount to 98.4 TWh in 2020 and between 75.2 TWh and 95.3 TWh in 2050, depending on the scenario (see Figure 9). This means that if the entire sustainable biomethane potential in France was allocated exclusively to HGVs, it could supply only 16.7% or 21.1% of the fleet's expected final energy consumption in 2050.



Notes: Comparing the final energy consumption of a dual-fual CI HPDI gas vehicle fleet with the total sustainable biomethane production potential in France. Assuming that all available biomethane potential is supplied to the transport sector, leaving nothing for the power, industry and heating sectors. A retail price of € 8.10/kg is more than 6 times the current price level of fossil methane as a propellant in transport.

Sources: Authors' calculations, Searle et al. (2018).

Figure 9: Sustainable biomethane production potential vs. final energy consumption of the PtM pathway

Additional costs for the fuel's liquefaction, distribution and storage are not yet included in the above retail price. This production volume would only be cost-viable with a very high subsidy level in order to reach a price comparable to fossil methane. Also, profit margins in the haulage industry are low and fuel costs make up a large part of total operating costs. If all this potential was allocated to the transport sector, no volume would be left for the power, industry and heating sectors and furthermore imply that the current consumers would no longer be permitted to use it. It should be considered unlikely that a notable share of the

[xvi] French-specific figures on biomethane potential were obtained from the study's authors.

biomethane potential would be allocated to the road freight sector when multiple sectors would be competing for the same limited production volume.

3.1.7. Summary and remaining gap

Combining all qualifying efficiency measures, and disregarding reciprocal effects between them due to changes in costs and demand (*ceteris paribus*, see section 2.1) would lead to significant emission reductions in the French inland freight sector. In order to provide for a conservative projection and not underestimate the level of future final energy consumption of GHG-neutral vehicles, the BAU fuel efficiency improvement of 30% by 2030 for both regulated and unregulated vehicle sub-groups was incorporated in the model (see also section 2 for a more detailed explanation). This and the UP scenarios of shift to rail and shift to inland waterways as well as increased logistics efficiency are included in the sum of efficiency measures. As stated above, fossil- and biomethane have been excluded from this due to their negligible emission reduction potential in the case of the former as well as intersectoral competition and non-competitive production costs in the case of the latter.

The results of the sum of efficiency measures are shown in Figure 10. They result in an 18% reduction in emissions by 2050 compared to 2018 emissions. Compared to the SNBC and ESR targets, which are determined from a 2005 baseline, total freight emissions are reduced by 33% to 21.5 Mt CO_2eq in 2030.

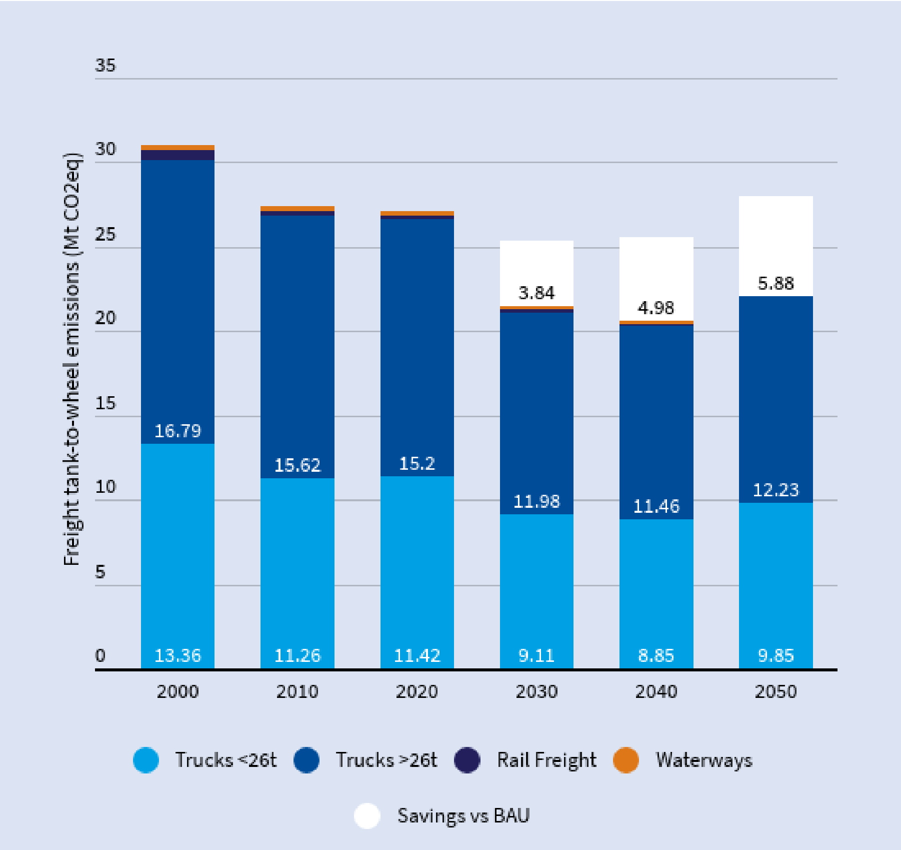


Figure 10: Infographic BAU vs. sum of qualifying efficiency measures

While this reduction goes a long way to enable France to meet its current 2030 ESR target, the trajectory shows that the qualifying efficiency measures will be far from sufficient to decarbonise the inland freight sector as it results in a total remaining gap of 22.07 Mt CO_2eq by 2050. It should be noted that the ESR target will likely need to be raised due to the expected increased ambition in the context of the European Green Deal. Also, some of these efficiency measures, such as the shift to rail and IWT scenarios, would require great effort and may eventually not materialise to that degree. This makes the decarbonisation of the road freight sector imperative, which will need to be addressed by an increased market uptake of GHG-neutral vehicles.

3.2. Closing the gap: options for different pathways to zero

If the sum of qualifying efficiency measures were fully implemented, France would fall short of its -37% ESR target by 2030. It is clear that increased efficiency and modal shift is not enough, as there remains a huge gap to -100% by 2050. Instead, it will be necessary to decarbonise the HGV fleet, and this transition must begin in the early 2020s. In the following section, the different technologies that can decarbonise road freight are presented and discussed. In the sections hereafter, the energy demand as well as the overall system costs and total cost of ownership of these technologies are presented and compared.

The pathways which technically qualify to bring about full decarbonisation of the vehicle fleet are:

1. direct electrification through overhead catenary and battery electric vehicles (OC-BEVs and BEVs)
2. hydrogen-powered fuel cell electric vehicles (FCEVs)
3. internal combustion vehicles fuelled by liquid electrofuels (ICEVs_PtL)
4. internal combustion vehicles fuelled by gaseous electrofuels (ICEVs_PtM)

The first two options require a rapid change and scale-up of drivetrain technology. The third pathway does not require a change of the drivetrain technology, as it is a drop-in fuel which would replace fossil diesel. The fourth option requires certain drivetrain modifications.

3.2.1. Market uptake and vehicle fleet penetration

Figure 11 illustrates the fleet penetration rates of new vehicle sales. In 2040, a phase-out for the sale of new fossil diesel vehicles for both HGV classes (above and below 26 t GCW) is imposed. For intermediate years, the share of GHG-neutral vehicles out of total new sales follows a linear increase. For the vehicle class up to a GCW of 26 t, a market uptake of exclusively BEVs is assumed (see section 3.2.2 below).

It should be noted that, for methodological reasons, the blending of fossil and synthetic diesel is not considered. In the model, ICEVs running on fossil diesel continue to do so for the rest of their lifetime. ICEVs_PtL are exclusively fuelled by synthetic diesel, while ICEVs_PtM run on synthetic methane only.

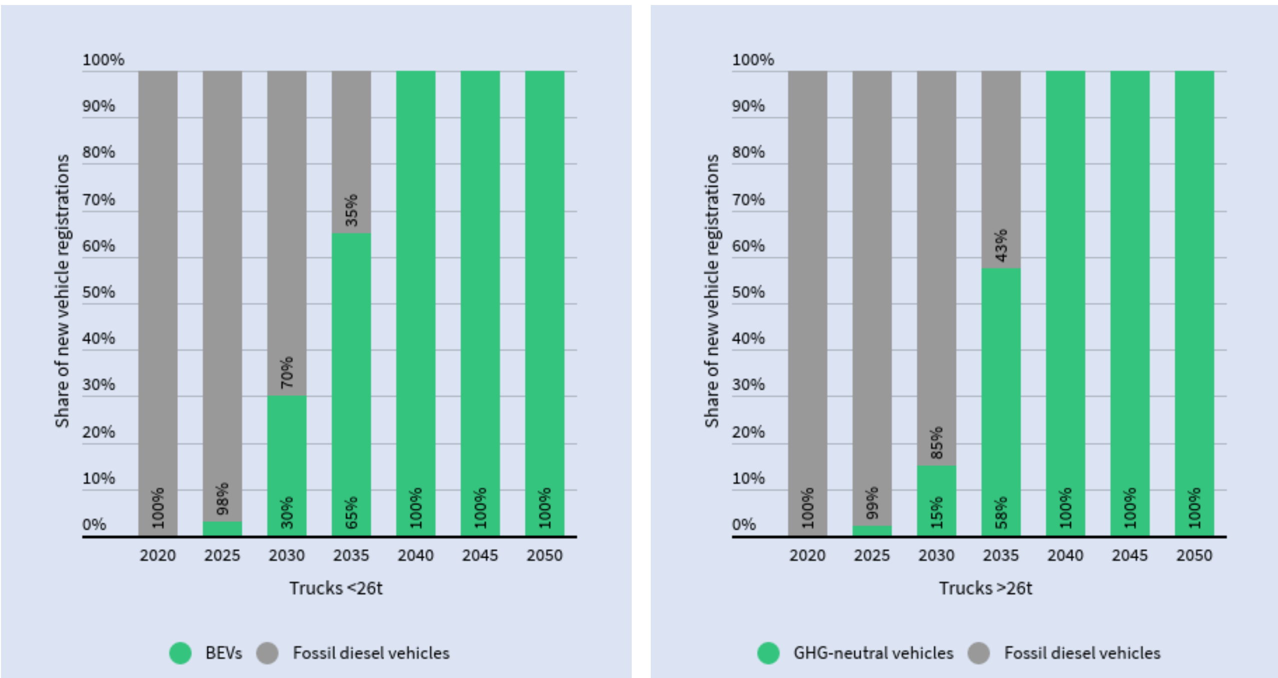


Figure 11: Share of new vehicle registrations

It is assumed that vehicle operations are replaced one for one, which means that load factor and mileage remain unchanged. Because the truck survival rates are the same across the pathways, the resulting tank-to-wheel emissions are the same too irrespective of the drivetrain technology. It should also be noted that the GHG-neutral vehicle uptake is on top of the sum of efficiency measures as described in section 3.1. In reality, a part of the 2030 fleet reduction target imposed by the CO_2 emission performance standards will be achieved by the deployment of ZLEVs (see section 3.1.1).

However, despite a 2040 sales phase-out for fossil diesel vehicles, Figure 12 shows that the uptake in GHG-neutral vehicles would not lead to zero GHG emissions by 2050. Instead, 2.3 Mt CO_2eq would remain due to the legacy fleet that would still be circulating at that time. It would therefore be necessary to enforce circulation limits on the legacy fleet and eventually ban them from the road (except for the ICEV_PtL pathway which would instead require a fossil diesel fuel phase-out, i.e. a 100 per cent blending quota for synthetic diesel). This would also lead to higher sales of GHG-neutral vehicles in order to cover the unmet transport demand. Opting for a phase-out of the circulating legacy fleet would lead to zero GHG emissions in 2050 and a total reduction of 28.0 Mt CO2eq compared to the BAU scenario. In terms of the ESR target, the emissions reduction in 2030 would amount to -38% compared to 2005.

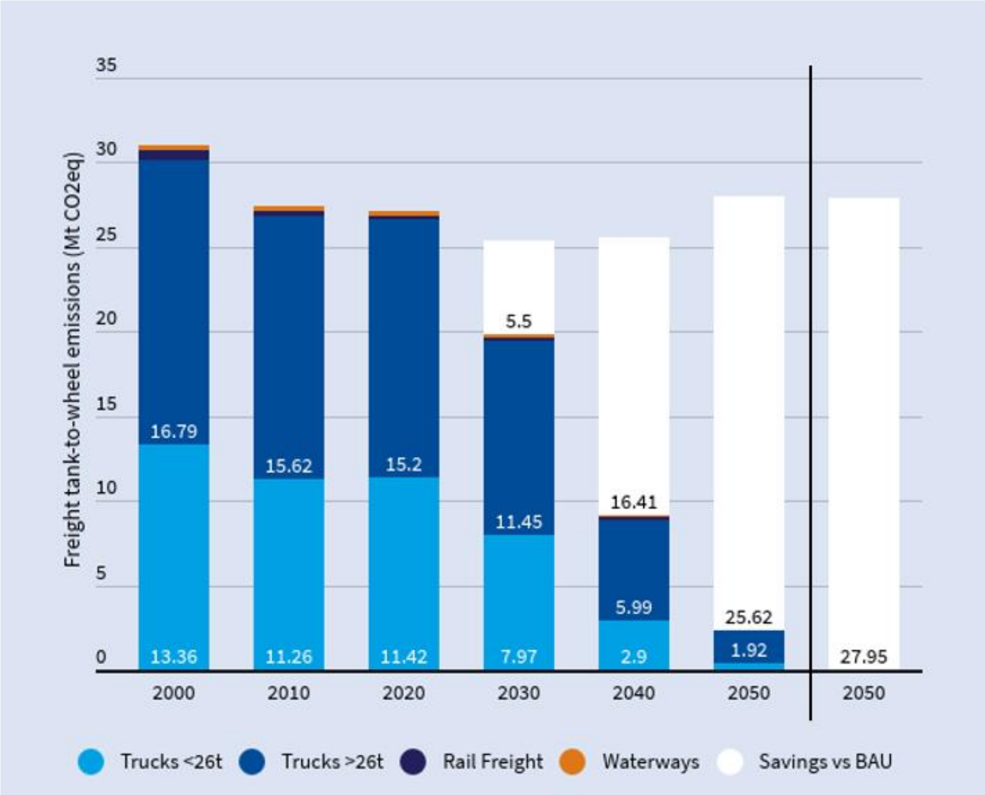


Figure 12: BAU vs. all qualifying efficiency measures and uptake of GHG-neutral vehicles as per Figure 11. The 2050 column to the right includes a legacy fleet ban

In 2020, the domestically registered vehicle fleet comprises a total of 263,000 lorries and tractors above 26 t (see section 1). Taking into account the development of road freight demand and its reduction through the sum of efficiency measures including modal shift to rail and IWT, the French HGV fleet above 26 t is expected to increase to around 344,000 vehicles by 2050.[xvii]

[xvii] It should be noted that this number excludes foreign registered commercial vehicles circulating on French territory which make up around 43% of the performed tkm. However, the EUTRM comprises a calibration between today's final energy consumption and number of domestically registered HGVs which is then carried forward until 2050 (see section 2.1).

3.2.2. Urban and regional delivery trucks

Depending on their intended purpose, commercial vehicles show differences in terms of their GCW and daily mileage. Lighter HGVs (3.5-16 t GCW) are commonly used for urban delivery applications. HGVs with a GCW of 16 to 26 t are mainly used for regional freight transport. Electrified urban- and regional delivery trucks up to 26 tonnes are available on the market today. Examples include Daimler's FUSO eCanter and eActros, Volvo's FL Electric and Renault's D Z.E.[124,125,126,127]

Trucks used for urban and regional delivery operations typically operate within one region or perform urban deliveries from nearby distribution centres. They have a typical daily range of 200 to 400 km. In France, 89% of road freight trips and 52% of vkm are less than 300 km.[128] Direct electrification of these vehicles based on an onboard battery is not only technically feasible but under certain conditions already today cheaper than fossil diesel from a total cost of ownership (TCO) perspective.[129]

In view of the techno-economic developments as well as market signals from truck manufacturers, it is reasonable to assume that, for the commercial vehicle segment with a GCW of up to 26 t, battery electrification is proving to be the most cost-competitive pathway in the mid and long-term. The model therefore makes the assumption that by 2030 30% and by 2050 100% of HGV sales with a GCW of up to 26 tonnes will be BEVs.

3.2.3. Long-haul trucks

Which drivetrain technology will prevail in the long-haul tractor sector (26 to 44 t GCW) is less clear. In the following section, the pathways are presented which qualify to decarbonise road freight. All of them are at the very beginning of the techno-economic learning curve and need to reach economies of scale to become cost-effective. After this section, the vehicle, fuel and infrastructure costs for the different long-haul pathways are compared.

3.2.3.1. Direct electrification

Direct electrification has the key advantage of being the most energy efficient, resulting in less primary and final energy use and thus reduced fuel costs. In the case of passenger cars and vans, a large-scale transition towards battery electrification is now widely regarded as the most cost-effective and fastest pathway to achieve full decarbonisation. The production capacities of electric light-duty vehicles (LDVs) are currently being scaled up and their market uptake will continue to accelerate. Upfront price parity of electric cars will be reached soon.[130]

The development of battery technology is advancing and manufacturing costs are falling. Net battery prices have reached a volume-weighted average of € 143/kWh in 2019, an 87% decrease since 2010, and this trend will only continue to prices as low as € 56/kWh in 2030.[131] It is expected that the chemical composition of battery cells, that is to say the cathode and anode materials and post-lithium chemistries, will be further optimised, thereby improving energy density, weight, lifetime and durability as well as enabling sustainable raw material sourcing and recycling.[132]

Direct electrification of HGVs, which can take the form of BEVs and OC-BEVs, provides for superior energy efficiency thanks to well-to-wheel conversion losses of less than 25%. Both use an electric drivetrain and a (differently-sized) battery to propel the vehicle but require different charging systems. Higher vehicle purchase costs, mainly due to the onboard battery, are compensated for by lower operating costs. Besides the energy efficiency argument, a drivetrain directly powered by electricity offers several advantages compared to conventional combustion engines. The vehicle emits no exhaust and thus eliminates CO_2 and air pollutant emissions at the tailpipe.[133] Also, an electric motor is made of fewer components and requires less maintenance and repairs in contrast to a thermal combustion engine.

3.2.3.1.1. Battery electrification

The market for BEVs is currently developing. Daimler's eCascadia with a maximum GCW of 36 t and a range of 400 km, and Tesla's Class 8 Semi with a likely similar but yet to be announced GCW and a range of up to 800 km are expected to enter series production for the U.S. market in 2020 and 2021 and shortly thereafter for the EU.[134,135] Nikola's Tre semi-truck with a GCW between 18 t and 26 t and a maximum range of 400 km is planned to enter series production in Europe in 2021.[136]

The drawbacks of battery electric propulsion in the long-haul segment are potential time losses due to longer charging times, the required infrastructure roll-out and, at the regional level, an increased power demand on the medium-voltage power grid. In contrast to liquid fuels, the lower energy density of batteries in terms of volume and mass poses challenges and can result in reduced payload capacity or range limitations.[137] Long-haul tractors require a large onboard battery for the required maximum daily range of up to 800 km. To achieve this, the BEV included in the cost analysis has a battery capacity of 1,200 kWh and a battery-to-wheel fuel consumption of 1.43 kWh/km (decreasing to 1.29 by 2030). In the future, the energy density of battery packs is assumed to increase to 318 Wh/kg by 2030 and 508 Wh/kg by 2050.[138] This would result in a gross additional vehicle weight of 6.6 tonnes in 2020, 3.8 t in 2030 and 2.4 t in 2050. When taking into account the extra two-tonne additional maximum weight allowance for ZEVs and the weight savings from replacing the conventional drivetrain with an electric one, this results in a net additional weight of two tonnes and, consequently, a payload penalty for the BEV in 2020. With increasing energy density of the battery, this penalty is no longer relevant from 2030 on.[xviii,139]

In terms of charging infrastructure, long-haul battery electric tractors, whose routes involve multi-day intercity travel, need extensive charging infrastructure along the motorway network. Charging can be done either overnight or through high-power charging points. High-power charging is aligned with EU rules on driving times and rest periods which foresee a mandatory break of 45 minutes every four and a half hours (and which can be split into two breaks of 30 and 15 minutes).[140] Kühnel et al. foresee overnight chargers with a power output of 150 kW to fully charge the battery, and mega chargers with an output of 1.2 MW to charge for a 400 km range (a driver can drive a maximum distance of 360 km between breaks at 80 km/h average speed).[141] It should be noted that such mega chargers would place significant additional power demands and require grid connection and likely the reinforcement of the medium-voltage grid. *CharIN*, the vehicle manufacturers' and industry's standardisation initiative, has started its work on developing a high-power charging standard for commercial vehicles (HPCCV) with 2 MW and more.[142]

3.2.3.1.2. Overhead catenary system

Downsizing the onboard battery and charging the vehicle dynamically during operation through an electric road system (ERS) on selected highly-frequented parts of the road network can provide for an alternative to static charging without renouncing the efficiency benefits of direct electrification. Both options can be deployed in a complementary approach, thus benefiting the market uptake of BEVs as well as OC-BEVs, since this would also encourage economies of scale and lead to synergy effects in the development of vehicle and charging technology as well as for upgrading the electrical grid.[143]

An ERS is providing the power supply via overhead catenary lines, a conductor rail in the ground, or inductive charging to the electric vehicle, and can offer a cost-effective and complementary solution to electrify the long-haul segment.[xix] European field trials are currently underway in Germany (overhead lines) and Sweden (one test for each technology).[144,145] Alstom has developed an ERS system with a conductor rail.[146] Generally speaking, all three different ERS technologies have their specific advantages and

[xviii] Authors' calculations.

[xix] Overhead lines can also be used by vehicles with hybrid electric drivetrains (OC-HEVs) as it is the case today for the field trials in e.g. Germany. This option was not considered in this study as hybrid diesel vehicles using ERS will likely be an exception after 2030. However, OC-HEVs may play an important role during the early market phase to achieve high utilisation rates of the overhead catenary infrastructure.

drawbacks, while some regard the overhead line concept as currently the most mature technological option.[147] The overhead catenary technology developed by Siemens and which is currently tested on three parts of the German motorway network was chosen for the subsequent cost analysis.[148,xx] Kühnel et al. provide cost estimations based on, inter alia, the ENUBA projects funded by the German Federal Environment Ministry.[149,150] The French Ministry for the Ecological and Inclusive Transition also undertook a socio-economic evaluation of an electric road concept back in 2017.[151]

The vehicles have a smaller onboard battery which can be charged while the vehicle is drawing power from the ERS and allows for electric autonomy when disconnected from the overhead lines. The OC-BEV included in the cost analysis has a battery capacity of 400 kWh allowing for a 250 km range. According to Wietschel et al., more than 95% of tractor-trailer trips off the German motorway are shorter than 100 km.[152] Bearing in mind a less dense motorway network in France, a range of 250 km should therefore be more than sufficient to bridge smaller and bigger electrification gaps and the distance between the motorway and the place of (un)loading. In line with Kühnel et al., an electrification degree of 90% was assumed, whereby the remaining 10% are due to gaps within the electrified parts of the network. Taking into account the mileage share on the electrified network (80%), this amounts to a 72/28% mileage split between electricity drawn directly from the overhead lines and from the onboard battery.[153]

The key market barrier of an ERS is the infrastructure development and, initially, higher capital expenditure costs. The technology needs to be harmonised across the EU Member States and its roll-out well coordinated between all involved stakeholders to ensure cross-border interoperability. Similarly to the charging infrastructure for BEVs, significant additional power demand would be placed on the medium-voltage power grid, requiring in parts grid reinforcement.[154] For example, Hacker et al. stress that, due to the expected unequal distribution of future renewable electricity generation across regions, some parts in the country could be more affected than others from a mismatch between electricity generation surplus and deficit.[155]

3.2.3.2. Hydrogen

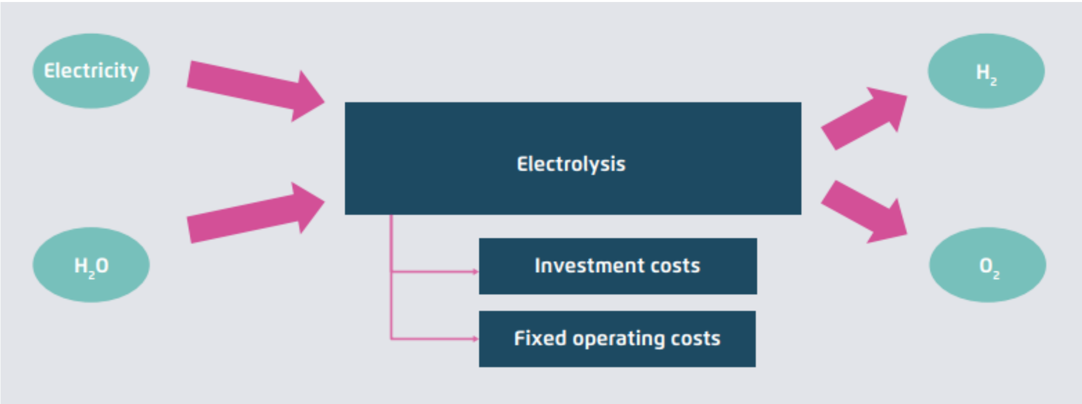
Hydrogen is considered as an energy carrier whose potential future applications include long-haul road freight. FCEVs are an alternative as they are GHG-neutral if the required hydrogen fuel is produced from additional renewable electricity. Nikola plans to produce the Tre also as an electric hydrogen model with a GCW of 40 tonnes and an estimated range of up to 960 km from 2023.[156,157] Hyundai has announced delivery of the first vehicles of the H_2 Xcient to the Swiss market in 2020 which features a 34 t GCW and a range of 400 km.[158] Hydrogen can be produced by an electrolyser which splits water into hydrogen and oxygen using electrical energy. The electro-chemical conversion in the vehicle's fuel cell then generates electricity which propels an electric motor. The advantages include the relatively high tank-to-wheel efficiency, short refuelling times, no tailpipe CO_2 and air pollutant emissions and potentially long driving ranges. The key challenges are the well-to-tank conversion efficiency losses, the high vehicle technology costs, the low volumetric density of hydrogen in terms of storage, the need to develop the necessary distribution and refuelling infrastructure, and an increased likelihood to rely on fuel imports from outside Europe due to higher renewable electricity demand, as explained in section 4.

FCEVs have a fuel cell system, a smaller onboard battery to buffer energy for engine peak loads and a storage tank with either compressed or liquefied hydrogen. Compression at 350 or 700 bar is the technically most mature and proven storage possibility but has disadvantages in terms of energy density and volume.[159] Compression at 700 bar offers a higher density than 350 bar and results in lower component costs compared to liquefaction. Liquefying the hydrogen would increase the storage density substantially but would also lead to additional energy losses between 25 and 35% and require more expensive cryogenic thick-walled

[xx] The overhead catenary system was also chosen for pragmatic reasons because it provides already for an extensive literature and cost estimations. This is currently hardly the case for the conductor rail system.

tanks.[160,161] For the cost analysis, a compressed fuel storage system at 700 bar was considered with a storage tank weight of 1.2 tonnes.

Hydrogen is today mostly produced from fossil gas through steam-methane reformation. It is possible to generate it from conventional electricity via electrolysis. Both techniques, so-called 'grey hydrogen', bear upstream GHG emissions (see also Table 2). To be GHG-neutral and classified as 'blue hydrogen', it requires the still immature and precommercial carbon capture and storage (CCS) technology. This leaves GHG-neutral hydrogen produced from renewable electricity, so-called 'green hydrogen', as the only viable production method.



Source: Frontier Economics (2018)

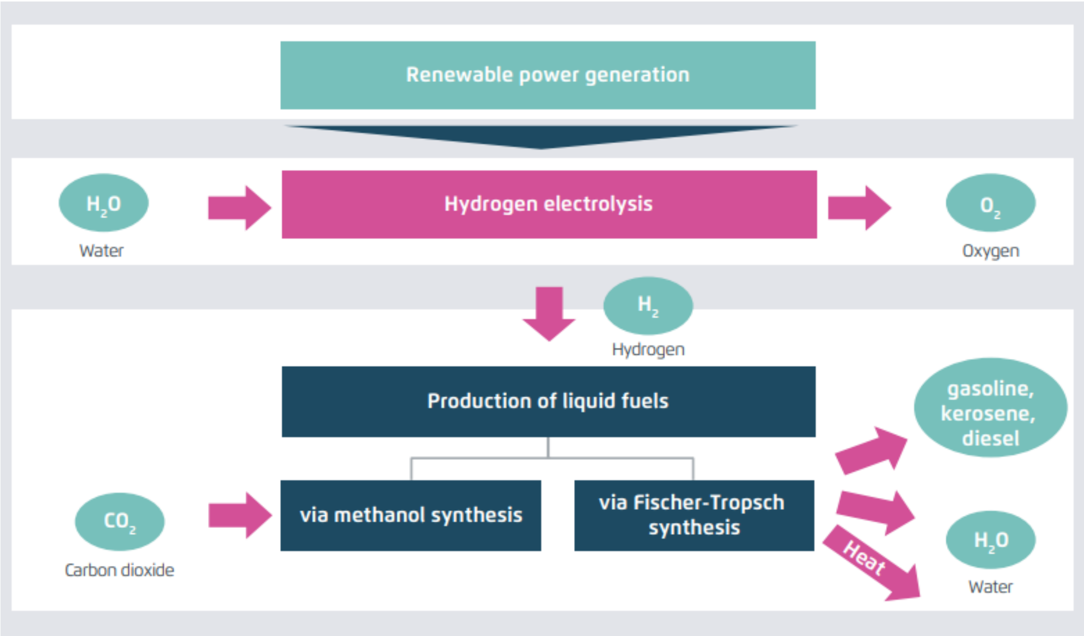
The idea to use excess renewable electricity to produce hydrogen in situations when renewables need to be curtailed due to grid bottlenecks or supply peaks is disputable. Different sources state that this would fail to provide the necessary load factor to operate the production facilities cost-effectively.[162] The lower the degree of utilisation the higher will be the share of investment expenditure as part of the total costs. For a scaled up electrolysis plant in the megawatt range, 2,800 full-load hours are considered realistic in order to provide for a load factor of 30 percent and reach a hydrogen cost level in the range of €-cent 7 to 12/kWh (€ 2.33 to 4.00/kg_{H2}) excluding transport and distribution costs.[163] Today, offshore wind facilities in the North Sea can reach more than 3,600 full-load hours on average and would therefore be suitable for the production of electricity-based fuels if their total electricity production was devoted to it.[164]

If the hydrogen is to be produced outside of Europe, it would need to be liquefied and transported via tanker to France which leads to considerable energy losses.[165] Other overseas transport options include the use of hydrogen carriers such as ammonia or liquid organic hydrogen carriers (LOHCs).[166] Unless an extensive hydrogen pipeline network was made available, the distribution from a production site or from a port of entry would likely be handled by high-pressure tube trailers delivering the liquefied hydrogen directly to the refuelling station where it can be used in liquid form or gasified again.[167,168] A network of refuelling infrastructure would need to be rolled out. There are currently less than 30 hydrogen refuelling stations operating in France, of which six offer hydrogen compressed at 700 bar and none in liquefied form.[169]

3.2.3.3. Power-to-Liquid

Power-to-liquid (PtL), that is to say synthetic diesel produced from green hydrogen and CO_2 through the Fischer-Tropsch (FT) synthesis, could theoretically provide for a GHG-neutral pathway to decarbonise long-haul road freight. The advantages of liquid FT-diesel are the mature and widely commercialised vehicle technology (i.e. making a drivetrain transition unnecessary) as well as the fuel's high volumetric storage density and the established distribution and refuelling infrastructure which could continue to be used. The key challenges are the high conversion efficiency losses during the fuel production process, the comparatively low thermal efficiency of the internal combustion engine, the resulting high fuel costs, the lack of meaningful air pollutant emission reductions and a greatly increased likelihood to rely on fuel imports from outside Europe from outside Europe due to significantly higher renewable electricity demand.[170]

The hydrocarbon-based liquid fuel is produced through the Fischer-Tropsch (FT) synthesis. The process requires hydrogen from additional renewable electricity and CO_2 from direct air-capture (DAC) as feedstock. CO_2 from DAC, i.e. capturing the greenhouse gas directly from ambient air, is the only viable method to ensure a closed CO_2 cycle without the accumulation of CO_2 in the atmosphere. Less-expensive carbon capture and utilisation (CCU) from an industrial point source cannot guarantee a closed CO_2 cycle and risks double-counting. As it is the case for hydrogen, PtL production plants require high utilisation rates in order to reach cost-effectiveness. Based on the Agora PtG/PtL calculator, the cost analysis assumes 4,000 full-load hours.[171]



Source: Frontier Economics (2018)

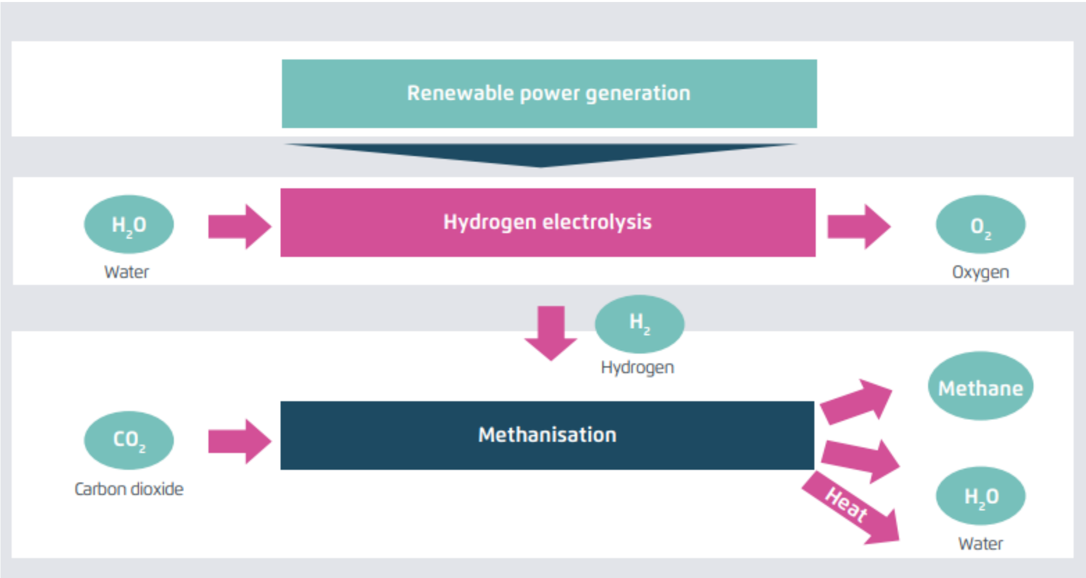
3.2.3.4. Power-to-Methane

Power-to-methane (PtM), that is to say synthetic methane produced from green hydrogen and CO_2 from DAC, could also theoretically provide for a GHG-neutral pathway to decarbonise long-haul road freight. The advantages of power-to-methane are the mature vehicle and storage technology and manageable engine adaptations which are required. Similarly to power-to-liquid, the key challenges are the high conversion losses during the fuel production process, the comparatively low thermal efficiency of the internal combustion engine, the resulting high fuel costs, the lack of meaningful air pollutant emission reductions and a greatly increased likelihood to rely on fuel imports from outside Europe due to significantly higher renewable electricity demand.[172] The low volumetric density of the gaseous fuel in terms of storage poses a further challenge. ICEVs_PtM would also require the deployment of new distribution and refuelling infrastructure. As of today, there are 55 operating LNG stations in France.[173]

The technicalities of ICEVs using methane as the propellant, which are discussed in section 3.1.5. on fossil methane, apply in the same manner to power-to-methane (engine efficiency, fuel storage, air pollutant emissions and necessary vehicle adaptations). For the reason that long-haul HGVs require a higher vehicle range, gas-powered trucks need to store their onboard fuel stored in liquefied form (LNG), which has further efficiency implications. As reported by Shell, 8% of the LNG produced is lost due to the required energy input during liquefaction.[174]

The hydrocarbon-based gaseous fuel is produced through methanation. The process requires hydrogen from additional renewable electricity and CO_2 from DAC as feedstock in order to generate methane and water as a by-product.[175] Similar to hydrogen and PtL, high utilisation rates are necessary to operate the production facilities cost-effectively. As for PtL, 4,000 full-load hours are assumed for the cost analysis.[176]

It should also be mentioned that opting for a PtM pathway carries significant risk of a potential fossil fuel infrastructure lock-in. Once vehicle manufacturers, hauliers and infrastructure operators would have made large-scale investments in the technology, they would have an inherent interest to prevent them from becoming stranded assets. In this scenario, the likelihood starkly increases that the involved stakeholders revert to fossil methane in order to fill the fuel supply gap.



Source: Frontier Economics (2018)

4. Additional renewable electricity demand

The different pathways are subject to different conversion efficiency losses and therefore need varying amounts of renewable electricity, either through direct electrification or as feedstock for the production of electricity-based fuels. Figure 13 below shows the average conversion efficiency rates for the different pathways based on today's and the maximum technical potential in 2050.[xxi] The differences between the pathways are evident. Direct electrification will always be - today and in the future - around twice as efficient as hydrogen, and around three times as efficient as internal combustion engines powered by electrofuels.

[xxi] The conversion efficiency rates in Figure 13 serve illustrative purposes and are to be understood as mean values taking into account different production methods. The calculation of electricity and fuel costs in the cost analysis (section 5) are based on the exact fuel production efficiencies of the Agora PtG/PtL calculator (well-to-tank) and the vehicle fuel consumption values (tank-to-wheel). Both can be found in Annex I.

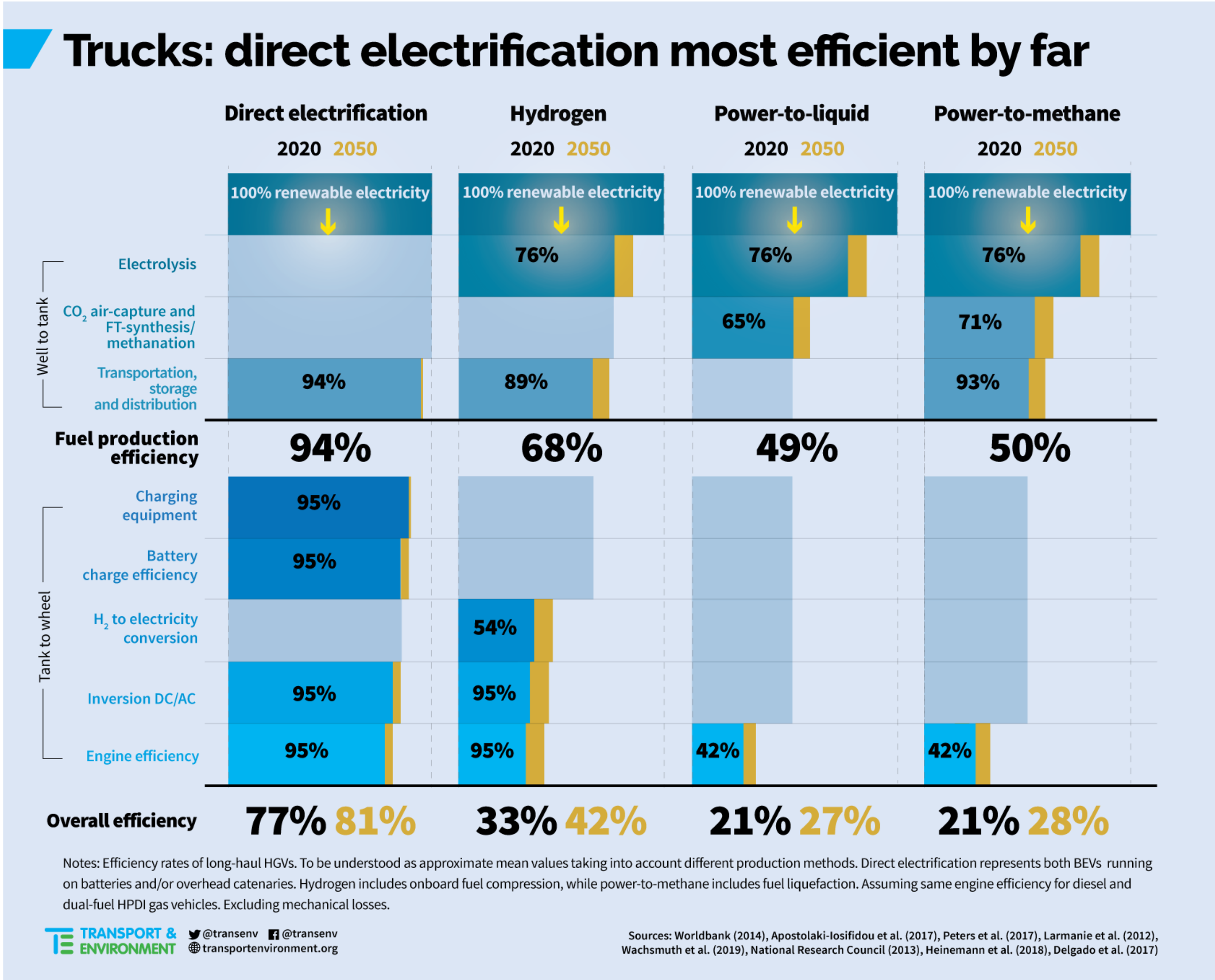
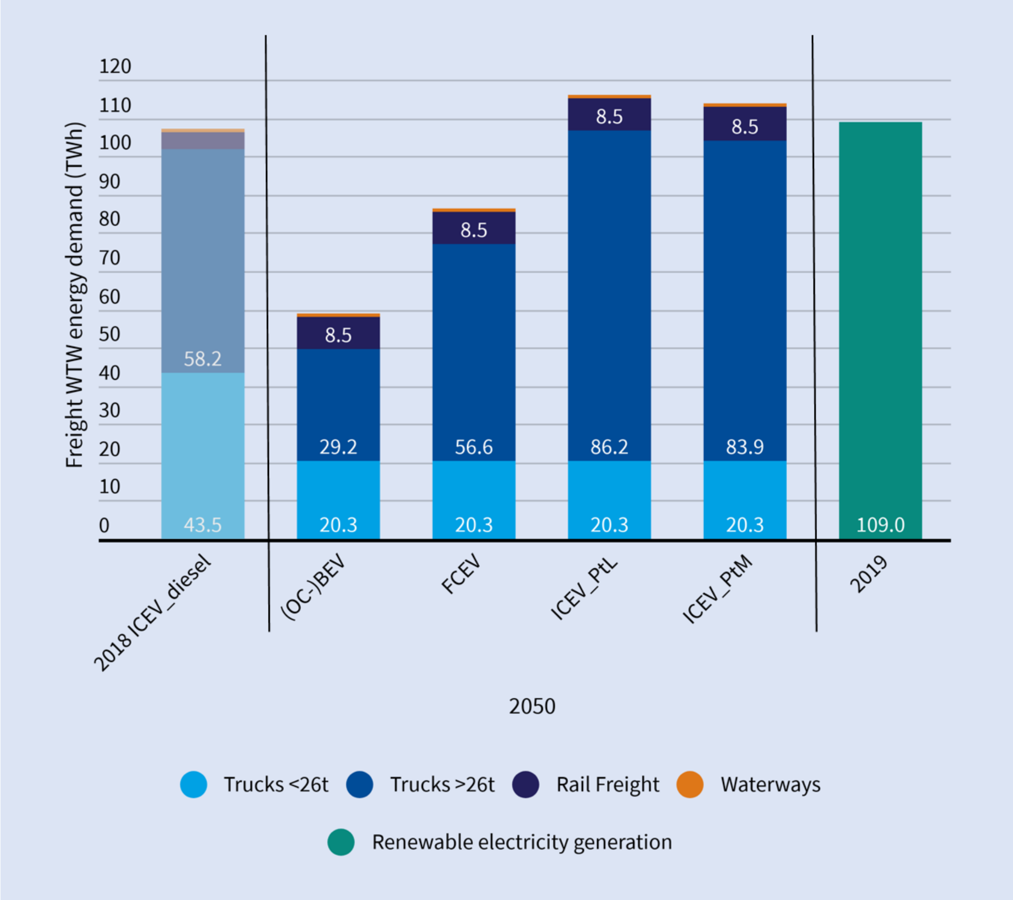


Figure 13: Conversion efficiencies of long-haul drivetrain technologies

This has an impact on the amount of renewable electricity needed for the different pathways. Figure 14 illustrates additional demand and compares the amount to the 2019 renewable electricity generation in France. To achieve full decarbonisation, this new renewable electricity will need to come from additional generation capacity. Battery electrification for all vehicles up to 26 t GCW is assumed across all pathways. The differences in total well-to-wheel renewable electricity demand are thus due to HGVs above 26 t. In 2050, the direct electrification pathway would require an equivalent of 54%, the hydrogen pathway of 79% and the two hydrocarbon pathways of 106% and 104% compared to the 2019 renewable electricity generation in France.[xxii]

[xxii] In this respect, it is again noted that the demand projections do not take into account possible interactions between modes due to changes in freight demand and transport costs, (i.e. *ceteris paribus*). Any change in freight demand due to price elasticity from changing transport and fuel costs is not fed back into the emissions modelling.



Sources: Authors' calculations, Réseau de Transport d'Électricité (2019).

Figure 14: Additional electricity demand compared to the freight sector's 2018 final energy consumption and 2019 renewable electricity generation in France

In the context of the wider energy transition and the imperative to fully decarbonise all economic sectors including the power, industry and heating sectors, substantial additional renewable electricity capacity will be needed in France. Because the decarbonisation of the aviation and shipping sector will rely on hydrogen and synthetic kerosene, direct electrification needs to take precedence over electricity-based fuels in road transport.

5. Cost analysis for long-haul trucks

The costs due to the renewable electricity demand are only one of the cost components which need to be considered. The system costs describe the total capital and operating costs for each vehicle, taking into account its purchase, fuel consumption and its refuelling or recharging infrastructure needs. The user costs, or total cost of ownership (TCO), describe the full purchase, ownership and operating costs including all taxes, levies, road charges and subsidies.

5.1. System costs

Unlike a TCO, the system costs refer to economic costs that need to be borne in one way or the other to a different degree by the manufacturer, the haulier, the consumer and the public sector. It excludes all taxes, levies and road charges except for electricity grid connection and network distribution fees in order to allow for a fair comparison with electricity-based fuels, since their transport and distribution costs are also included.

5.1.1. Vehicle costs

The vehicle costs are mostly based on Kühnel et al. and can be found in Annex II.[177,xxiii] All vehicles across the pathways have the same characteristics required to meet the typical application profile of a long-haul tractor (see Table 3). The main criterion is that the vehicle reaches an operational range of 800 km per day, the maximum one driver can drive (see section 3.2.3.1.1). Practically all tractors registered in France have a GCW of 44 t.[178] All vehicle component costs are kept constant beyond 2030 and until 2050.

Kühnel et al. undertook a bottom-up cost estimation for the different vehicle components and included a mark-up factor of 1.4 to determine the net retail price after manufacturing and distribution costs. The total net retail price (excl. vehicle tax and VAT) include the applicable costs due to the glider, conventional drivetrain (incl. internal combustion engine and exhaust aftertreatment system), electric motor, fuel cell system, fuel tank system, battery and pantograph. Maintenance & repairs refer to costs due to general servicing, the urea solution for the exhaust aftertreatment system and the pantograph. The net retail price for the BEV also considers opportunity costs due to the additional vehicle weight and lost payload until 2030.

	ICEV_diesel	BEV	OC-BEV	FCEV	ICEV_PtL	ICEV_PtM
Engine technology	Diesel motor	Electric motor			Diesel motor	Dual-fuel CI HPDI
Engine power	350 kW					
GCW	40/44 t					
Annual mileage	120,000 km					
Maximum daily range	> 1,700 km	~ 800 km on battery	> 800 km (~ 250 km on battery)	~ 800 km	> 1,700 km	800 - 1,100 km
Fuel storage system	Diesel tank	Battery		compressed H_2 tank (700 bar) and battery	Diesel tank	cryogenic LNG tank and diesel tank
Fuel tank and battery capacity	570 litres$_{diesel}$	1,200 kWh	400 kWh	55 kg$_{H2}$ 70 kWh	570 litres$_{diesel}$	205 kg$_{LNG}$ 170 litres$_{diesel}$

Table 3: Long-haul tractor vehicle specifications

5.1.2. Fuel costs

The Agora PtG/PtL calculator was used to calculate the levelised cost of electricity (LCOE) and the cost of synthetic electrofuels produced from additional renewable electricity capacity.[179] In terms of the lifecycle climate performance of renewable electricity and synthetic electrofuels, emissions incurred from the construction of production facilities are not taken into account.[180] Likewise, any potential time-related constraints to the deployment of fuel production facilities are disregarded and it is assumed that the

[xxiii] The cost assumptions made by Kühnel at el. are based on the German cost level. Since the price level and purchase power in the two countries are broadly similar, the costs should be comparable.

additional final energy consumption of HGVs is met with an increasing generation and production capacity without any limitations. The detailed cost components can be found in Annex II.

Depending on the chosen cost scenario, the electricity generation and fuel production facilities are either based in the North Sea (NS) or in North Africa (NA). The electricity for the direct electrification pathway of BEVs and OC-BEVs is in both scenarios produced from offshore wind in the North Sea.

The fuel costs are based on the reference scenario of the Agora PtG/PtL calculator. For both the NS and NA scenarios, the chosen weighted average cost of capital (WACC) is 6% and the method of CO_2-extraction is direct air-capture.[181] Offshore wind in the NS scenario was set at 4,000 full-load hours per year. The same applies to the high-temperature SOEC electrolysis.[xxiv,182] Solar PV in the NA scenario was set at 2,344 full-load hours as it is the case for electrolysis.[xxv] In both scenarios, the FT-synthesis and methanation process were set at 4,000 full-load hours (which requires temporary hydrogen storage in the NA scenario).

Grid connection fees are included in the LCOE in both scenarios for all pathways. In addition, the electricity pathway includes the *Tarif d'utilisation du réseau public d'électricité* (TURPE) to account for electricity network distribution costs in France. The synthetic fuels pathways take into account costs due to liquefaction, transport via tanker from North Africa to France (Marseille) and domestic distribution until they reach the refuelling station. Apart from this, no other taxes or levies on electricity and fuels are considered in order to allow for an undistorted assessment of the real fuel costs.

For the PtM pathway, the chosen engine technology is a dual-fuel CI HPDI gas engine for which the same fuel efficiency as conventional diesel engines was assumed. No additional energy losses due to boil-off or venting are considered. Although an estimated 10% of the vehicles' fuel consumption is due to diesel to ignite the fuel-air mix, for simplicity the emissions modelling and cost analysis assume that these vehicles run on methane only.

5.1.3. Infrastructure costs

The estimated infrastructure costs are also based on Kühnel et al. They take into account the size and power of the refuelling and charging stations, the utilisation rate, service life, capital expenditure, operational expenses and the number of supplied vehicles per station. The costs are kept constant from 2020 until 2050. The detailed cost components can be found in Annex II.

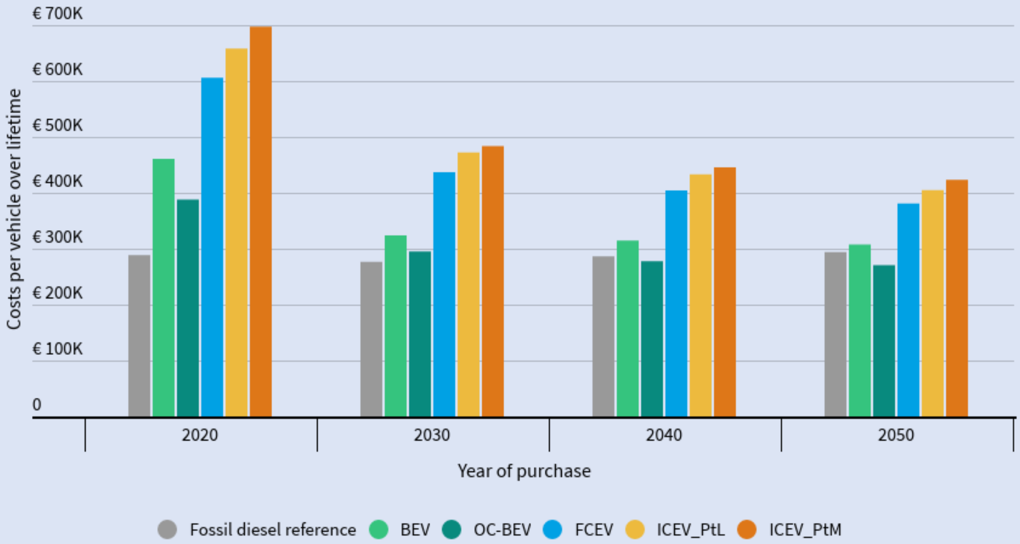
The fossil diesel reference and the PtL pathways can use the already established refuelling infrastructure. For the sake of simplicity, it is assumed that the investment costs of these petrol stations are already written off and the infrastructure does not need to be replaced after its service life ends.

5.1.4. Results

The lifetime system costs per new vehicle for the NS and NA scenario are shown in Figure 15 and 16 and include the fossil diesel reference pathway to allow for comparability. The lifetime system costs take into account a vehicle use period of five years and the remaining residual value of the vehicle. As mentioned, the system cost approach permits for a calculation of the true techno-economic costs of the different pathways and should not be confused with a TCO, which will be presented in the following section.

[xxiv] Proton-conducting solid oxide electrolysis cells (SOEC), which show the lowest level of conversion losses, are the least developed electrolysis technology and are currently at a pre-commercial stage. The technology was chosen for the cost analysis to account for the maximum technical potential.
[xxv] It is also possible to combine PV and wind power in the NA scenario instead of PV alone, which would then allow for a higher number of full-load hours. However, LCOE from wind is higher than for PV and a combination of both would result in higher fuel costs than from PV alone according to the Agora PtG/PtL calculator.

Lifetime system costs of long-haul trucks in France North Sea scenario

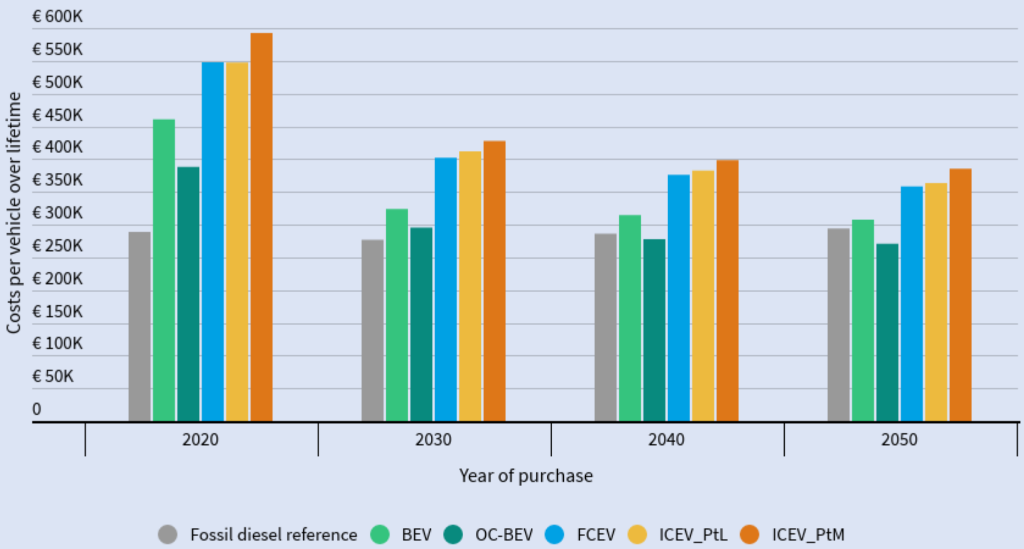


Notes: Assuming a first use period of 5 years. Including total vehicle costs (incl. maintenance & repairs and residual value), fuel costs and infrastructure costs (at full utilisation). Excluding taxes, tolls and road charges except for grid connection fees and electricity distribution costs.

Sources: Authors' calculations, Kühnel et al. (2018), Frontier Economics (2018), Mottschall et al. (2019), Meszler et al. (2018), BloombergNEF (2019), Ricardo Energy & Environment (2019), Observatoire de l'industrie électrique (2019).

Figure 15: Lifetime system costs of long-haul HGVs - North Sea scenario

Lifetime system costs of long-haul trucks in France North Africa scenario



Notes: Assuming a first use period of 5 years. Including total vehicle costs (incl. maintenance & repairs and residual value), fuel costs and infrastructure costs (at full utilisation). Excluding taxes, tolls and road charges except for grid connection fees and electricity distribution costs. For (OC-)BEVs, the renewable electricity generation is taken from the North Sea scenario.

Sources: Authors' calculations, Kühnel et al. (2018), Frontier Economics (2018), Mottschall et al. (2019), Meszler et al. (2018), BloombergNEF (2019), Ricardo Energy & Environment (2019), Pfennig et al. (2017), Observatoire de l'industrie électrique (2019).

Figure 16: Lifetime system costs of long-haul HGVs - North Africa scenario

The results show that BEVs and OC-BEVs represent the most cost-effective option amongst all pathways which can achieve zero well-to-wheel emissions by mid-century. OC-BEVs will reach cost parity with the fossil diesel reference pathway as early as 2037 disregarding taxes, levies and charges. BEVs and OC-BEVs are even then cheaper to own and operate than FCEVs and ICEVs running on synthetic diesel or methane if those electricity-based fuels are produced in North Africa and shipped to France.

5.2. Total cost of ownership

The total cost of ownership (TCO) comprises the system costs and all taxes and levies on vehicle purchase, operation and fuel as well as road charges. In this sense, the TCO describes the total expenses for a haulier.

5.2.1. Taxes, levies and road charges

As explained above, the system costs already include grid connection fees for the renewable electricity generation facilities as well as costs for transport and distribution infrastructure for both electricity and fuels. In addition to this, the TCO includes all taxes and levies excl. VAT on the purchase and use of the vehicle and the final fuel end product. This means that electricity-based fuels are taxed only once.

The taxes on vehicle purchase and operation include the one-time registration tax and additional parafiscal charge as well as the annual special tax on certain motor vehicles.[183]

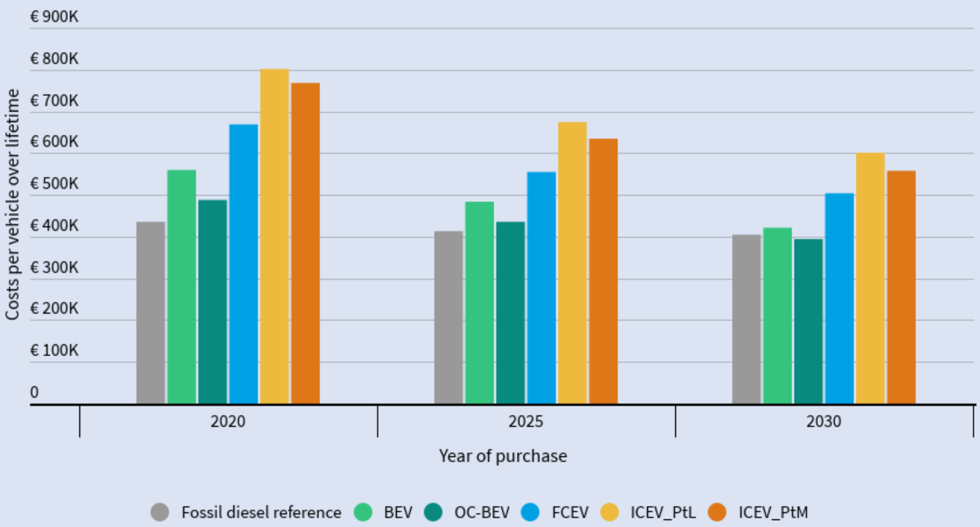
For the fossil diesel reference as well as the power-to-liquid pathway, today's diesel excise duty rate of €-cent 59.40/litre minus the fuel rebate of €-cent 15.71/l is taken into account and kept constant until 2030. For the electricity pathway, the *Contribution tarifaire d'acheminement* (CTA), *Contribution au Service Public d'Electricité* (CSPE) and *Taxes sur la Consommation Finale d'Electricité* (TCFE) is included. For the hydrogen pathway, the current tax exemption is maintained. For the power-to-methane pathway, the reduced *Taxe intérieure de consommation sur le gaz naturel* (TICGN) of € 5.23/MWh for the use as transport propellant is applied.[184]

In line with 2018 road charge estimations by the Comité National Routier, an average toll cost of €-cent 10.64/km for a long-haul truck with an annual mileage of 120,000 km was assumed.[185] This is applied across all pathways because the majority of the tolled motorways in France is managed by concessionaires and a meaningful reduction on the infrastructure charge for ZEVs based on the Eurovignette Directive will therefore be limited to substantially amended or renewed concessions and the publicly-managed part of the road network (see section 1.3 and 7.2).

5.2.2. Results

The lifetime TCO per new vehicle for the NS and NA scenario is shown in Figure 17 and 18. It takes into account a first use period of five years and the remaining residual value.

Total cost of ownership of long-haul trucks in France North Sea scenario

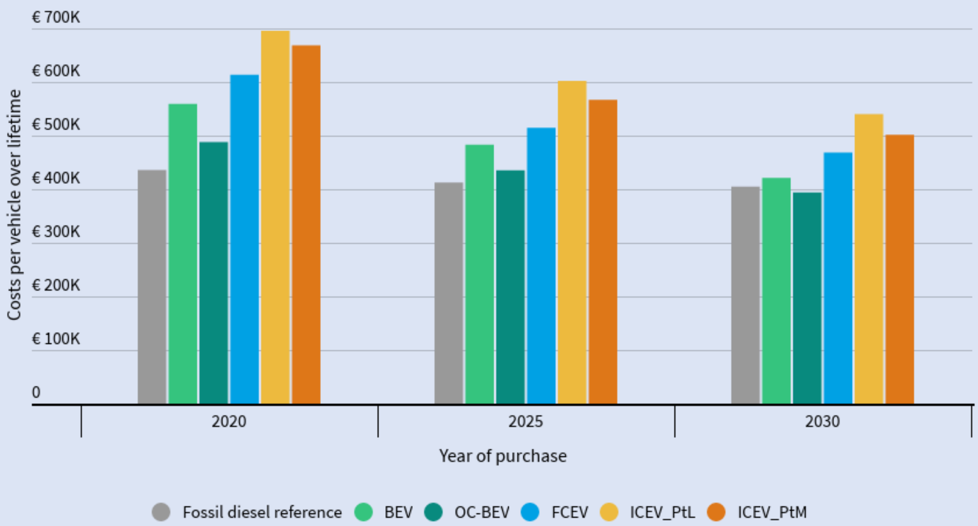


Notes: Nominal prices excl. VAT. Assuming a first use period of 5 years. Including total vehicle costs (retail price and residual value, maintenance & repairs, vehicle taxes, excl. financing costs), fuel costs (incl. grid connection fees, transport & distribution costs and taxes & levies), infrastructure costs (at full utilisation) and road charges.

Sources: Authors' calculations, Kühnel et al. (2018), Frontier Economics (2018), Mottschall et al. (2019), Meszler et al. (2018), Delgado et al. (2017), Moultak et al. (2017), BloombergNEF (2019), Ricardo Energy & Environment (2019), Ministère de la Transition écologique et solidaire (2020), Observatoire de l'industrie électrique (2019), Energie-Info (2020), Weekly Oil Bulletin (2020), ACEA (2019).

Figure 17: TCO of long-haul HGVs - North Sea scenario

Total cost of ownership of long-haul trucks in France North Africa scenario



Notes: Nominal prices excl. VAT. Assuming a first use period of 5 years. Including total vehicle costs (retail price and residual value, maintenance & repairs, vehicle taxes, excl. financing costs), fuel costs (incl. grid connection fees, transport & distribution costs and taxes & levies), infrastructure costs (at full utilisation) and road charges. For (OC-)BEVs, the renewable electricity generation is taken from the North Sea scenario.

Sources: Authors' calculations, Kühnel et al. (2018), Frontier Economics (2018), Mottschall et al. (2019), Meszler et al. (2018), Delgado et al. (2017), Moultak et al. (2017), BloombergNEF (2019), Ricardo Energy & Environment (2019), Ministère de la Transition écologique et solidaire (2020), Observatoire de l'industrie électrique (2019), Energie-Info (2020), Weekly Oil Bulletin (2020), ACEA (2019).

Figure 18: TCO of long-haul HGVs - North Africa scenario

Also when accounting for all taxes, levies and road charges, BEVs and OC-BEVs represent the most cost-effective option amongst the pathways. Disregarding potential subsidies for ZEVs, OC-BEVs will reach cost parity with the fossil diesel reference pathway in 2029 and BEVs in 2039. And again, the electric drivetrain options are cheaper to own and operate compared to FCEVs and ICEVs running on synthetic diesel or methane if those electricity-based fuels are produced under optimal production conditions in North Africa and shipped to France. It is also worth noting that the above TCO already includes a tax exemption for hydrogen and a significant tax break for methane, but no subsidies for electricity used as a transport fuel (see section 7.3).

6. Conclusion: the optimal pathway

It follows that battery electric vehicles in general and those using an overhead catenary infrastructure in particular are the most cost-effective pathway to replace the current fossil diesel-powered fleet and achieve zero inland freight emissions in France by 2050. A modal shift away from the road and towards rail and inland waterway freight is to an extent possible. However, this limited potential should not be overestimated given that, in the model's UP scenarios, freight capacities already increase by 84% (rail) and 100% (waterways). In the medium-term, the sum of qualifying efficiency measures can contribute a great deal to bring down inland freight emissions in France. But they are not sufficient to reach the 2030 target, let alone decarbonise the sector in the long-term. A drivetrain transition towards direct electrification for urban, regional delivery and long-haul trucks will be indispensable if the country wants to meet its binding 2030 and 2050 climate targets at the least cost for the public sector, businesses and the consumer.

7. Policy recommendations

Both French and EU policy measures adopted and implemented as of today will curb emissions but fall short of the magnitude of political ambition which will be needed to reach the 2030 and 2050 targets. The findings of this study should prompt lawmakers, both in France and on the EU level, to take swift and decisive regulatory action.

The recently adopted mobility law requires the French government to develop a rail freight strategy before 2021.[186] On this occasion, we call on the French government to simultaneously work on and publish a road freight strategy which shall set out a credible pathway towards decarbonisation including intermediate emission reduction targets in line with the SNBC and the ESR and concrete policy measures to achieve this.

7.1. Taxation reform

Electricity taxation

There are currently no reduced tax rates foreseen for electricity used in road freight transport. A reduced CSPE rate of € 0.5/MWh (instead of € 22.5/MWh) is currently granted to the transportation of passengers by train, metro, tramway, electric bus and goods by train.[187] This provision should be extended to the transportation of goods by road vehicles directly propelled by electricity, which includes BEVs and OC-BEVs.

A reduced CSPE rate for (OC-)BEVs alone would reduce their TCO by up to 5% (depending on the year). The incentive would bring forward TCO price parity with the fossil diesel reference pathway to 2026 for OC-BEVs (from 2029) and 2030 for BEVs (from 2039).

Methane taxation

France is currently applying an extremely low excise duty rate to fossil methane as transport propellant (€ 5.23/MWh) which is lacking conceivable justification when considering the negative climate and air quality impact (see section 3.1.5). The full TICGN rate for fossil gas for household consumption amounts to € 8.45/MWh. As a bare minimum, at least the full rate should also be applied to fossil methane as a transport propellant. Biomethane is currently exempt from the TICGN irrespective of its feedstock origin and GHG emissions savings potential. This exemption should cease to apply unless a vehicle is running exclusively on advanced waste- and residue-based biomethane, is being refuelled at local biomethane production sites and the vehicle operator can verify the compliance with these rules.

Diesel fuel rebate

The diesel fuel rebate should be phased out as soon as possible. The currently low oil prices are a good opportunity to make progress towards this goal. As this would disproportionately affect domestic hauliers more than their foreign competitors due to fuel tourism, part of the additionally generated tax revenue could go to a new investment fund to provide purchase subsidies to small- and medium-sized haulier companies who wish to invest in zero-emission trucks (see below). In practice, the additional revenue would be earmarked and go directly to the AFITF to set up such a purchase subsidy scheme.

The **French carbon tax,** which remains frozen at its 2018 level (€ 44.6/tCO_2), should be increased again as it was initially foreseen. The successive harmonisation of petrol and diesel excise duty rates, also currently on hold, should be resumed too.

The French government should undertake these taxation reforms through the upcoming **2021 budget law** in order to improve the TCO for zero-emission trucks and abolish environmentally harmful subsidies.

EU Energy Taxation Directive

The Directive sets a minimum excise duty rate for natural gas used as transport propellant. At the same time, however, it gives Member States the possibility to apply total or partial exemptions to this minimum rate, thereby effectively nullifying it.[188] This provision needs to be phased out in the upcoming revision.[189]

7.2. Road charging

Currently, HGVs are not charged for the use of the publicly-managed road network. With a view to internalise a greater share of externalities, the French government should therefore introduce a distance-based toll scheme for all trucks with a GCW above 3.5 t circulating on publicly-managed roads. A time-based system (i.e. a vignette) would fail to deliver the necessary steering effect and run contrary to the polluter pays principle. The scheme needs to comply with the rules of the currently ongoing revision of the Eurovignette Directive and include a meaningful reduction of the infrastructure charge for ZEVs as well as introduce external cost charges for air and noise pollution. In regards to the privately-managed road network and the motorway concessions, the rules of the revised Directive will need to be applied as soon as the concession contracts are substantially amended or renewed. Here too, France should opt for external cost charges in the future.

7.3. Purchase incentives for zero-emission trucks

Today's still higher upfront purchase costs are deterring hauliers from investing into ZEVs despite lower operating costs compensating for them during the vehicle's operation. In order to incentivise the purchase of ZEVs and accelerate the market uptake, meaningful purchase subsidies are needed. Once ZEVs have reached a certain market share, the support instruments could be rolled back again. As a general rule, any ICE vehicles including gas trucks should not benefit from any such direct or indirect subsidies.

The special depreciation system in France for HGVs running on natural gas was extended to battery electric- and hydrogen-powered vehicles and, in addition, prolonged until the end of 2021. Under this scheme, vehicle owners can depreciate a total of 160% (GCW up to 16 t) or 140% (GCW above 16 t) from the purchase value if the truck is propelled by fossil-, biomethane, electricity or hydrogen.[190] Although the scheme can, in principle, provide for a fair reduction of the increased vehicle costs, it can only have the intended effect if hauliers generate sufficiently large earnings before taxes and do so over the complete vehicle's linear amortisation period. However, profit margins are known to be low in the haulage industry. And even if they were high enough to allow for the tax deduction, the tax advantage is spread over the vehicle's total use period. It has to be expected that this scheme fails to sufficiently encourage operators to shoulder the increased upfront purchase costs of ZEVs.

For this reason, France should introduce a time-limited direct purchase subsidy for battery electric- and hydrogen-powered trucks as it was done by the German Federal Transport Ministry. Under the current German funding regulation, operators can receive grants of up to € 12,000 (GCW up to 12 t) and € 40,000 (above 12 t) per vehicle, whereby a maximum 40% of the additional vehicle investment costs are covered and the maximum funding a single company can receive through the scheme is capped at € 500,000.[191] Germany is planning to increase the purchase subsidy rates in 2020.[192] The Federal State of Baden-Württemberg provides a maximum grant of € 100,000 covering a maximum 50% of the extra vehicle investment costs.[193] California is providing purchase funding rates going as high as $ 150,000 for HGVs above 15 t GCW.[194] A French purchase subsidy should therefore come with high enough rates to maximise the steering effect. Any funding scheme should be limited to ZEVs and not apply to gas-powered trucks. The same goes for currently existing regional funding schemes for purchasing commercial gas vehicles.[195] French cities and regions should end such schemes as soon as possible.

An illustrative ZEV purchase subsidy based on the current German funding rates alone would reduce the TCO of (OC-)BEVs by up to 9% and of FCEVs by up to 5% (depending on the year). The incentive would bring forward price parity with fossil diesel to 2027 for OC-BEVs (from 2029) and 2030 for BEVs (from 2039).

Taxation reform and purchase incentives: impact on the TCO

Combining the reduced CSPE tax rate for (OC-)BEVs, a phase-out of the fuel rebate phase-out after 2020 and an illustrative ZEV purchase subsidy would help a great deal to accelerate the transition towards ZEVs (see Figure 18). Such a taxation reform and incentive package would reduce their TCO by up to 14%, while increasing the fossil diesel's TCO by up to 5% (depending on the year). It would thereby bring forward price parity with fossil diesel to 2020 for OC-BEVs (from 2029) and to 2024 for BEVs (from 2039).

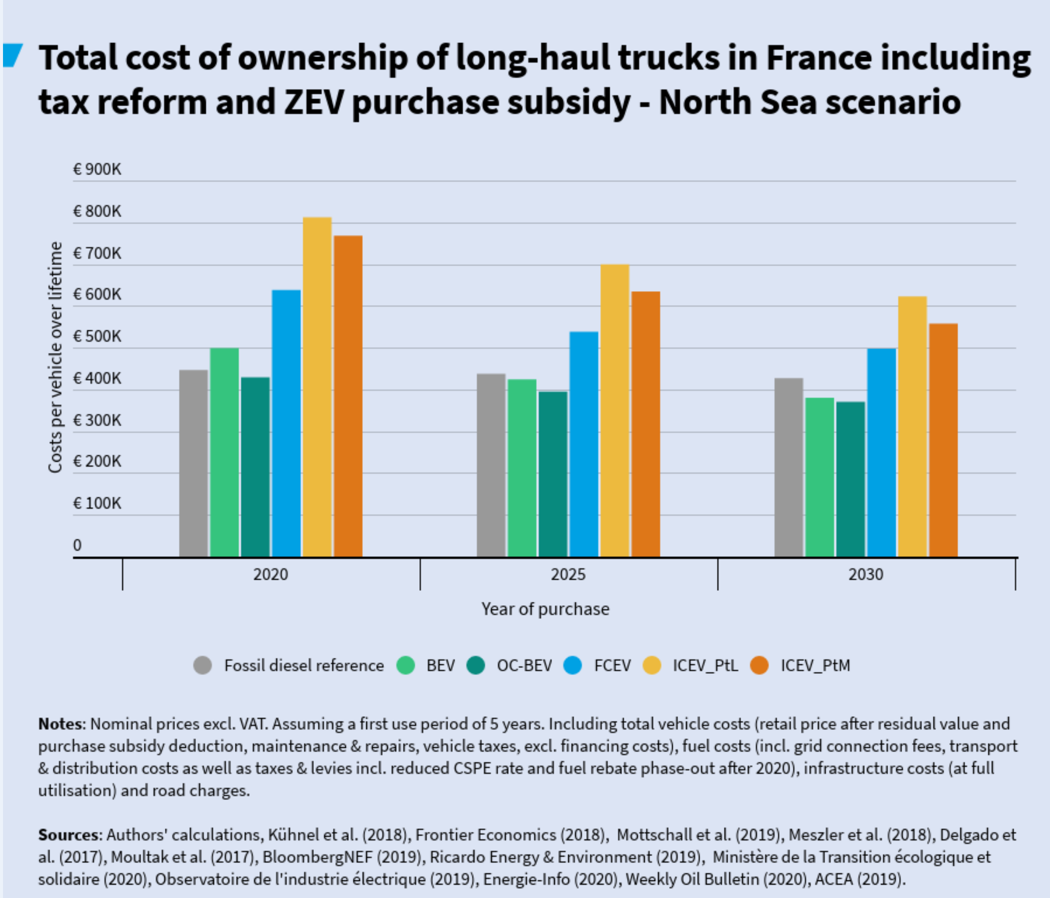


Figure 19: TCO of long-haul HGVs including tax reform and purchase subsidy - North Sea scenario

7.4. Charging infrastructure

Funding and financing schemes for private companies

France should end the incentives and drop the targets included in its NECP for developing refuelling infrastructure for CNG and LNG vehicles, and shift its focus towards incentivising the infrastructure development for ZEVs. The French government should advance a formal strategy laying out its intentions how to support and ramp up the deployment of private and (semi) public charging infrastructure for urban-, regional delivery- and long-haul trucks as it was similarly done by Germany and California.[196,197] The French government should introduce funding instruments which support transport companies and the logistics sector in installing private and shared infrastructure for depot and destination charging for urban and regional delivery trucks.

Such programmes should also involve utility companies and provide explicit funding to upgrade the electricity distribution grid, since fleet operators are often unable to bear the additional infrastructure investment costs. For example, California requires the state's utility providers to undertake the necessary grid upgrades for transport-related electrification activities including vehicle charging.[198] As a result, utilities offer the infrastructure upgrades at no additional cost for the operator. [199]

Public-private partnerships

The formation of public-private partnerships with truck manufacturers and logistics companies, such as the *Volvo LIGHTS* project in California, can help overcome initial funding restraints, facilitate the knowledge flow between stakeholders and advance systematic approaches to electrify integrated supply chain networks.[200]

France could consider setting up one or more public-private partnerships with vehicle manufacturers and utility companies focusing specifically on public high-power charging infrastructure (HPCCV) for regional and long-haul operations along the highly-frequented road network. National public funding could be combined with EU funding through the Connecting Europe Facility (CEF) and other EU funding and financing instruments such as Horizon Europe and InvestEU.[201]

Electric road systems

With regard to electric road systems (ERS), France's commitment to intensify the coordination with like-minded Member States such as Germany and Sweden is particularly welcome.[202] It now requires concrete political action and closer collaboration between the EU and its Member States. Currently, the greatest barrier for ERS deployment is the lack of technological harmonisation. What is also needed is further analysis on the cost differences between overhead catenary, conductive and inductive charging systems. It is in the interest of all Member States involved, to develop a mutual understanding on the required steps towards harmonisation in order to ensure cross-border interoperability and the technology's long-term success perspective. France, together with Germany and Sweden as the two most engaged Member States, should select the most competitive and mature technology and establish it as the new commonly-agreed European standard.

Once this decision has been taken, the involved Member States should establish a coordination mechanism together with industry stakeholders in order to further the technology's development and ramp up its deployment along the TEN-T core network with a view to 2030. As a first concrete step, France should soon initiate a larger, cross-border field trial project together with Germany to test the potential impact on the electricity grid and cross-border traffic flows. This would also help alleviate concerns over the technology's EU-wide interoperability.

Revision of the Alternative Fuels Infrastructure Directive

The revision of the Directive on the Deployment of Alternative Fuels Infrastructure (AFID) in the beginning of 2021 should focus on zero-emission technology only.[203] Current infrastructure targets for CNG and LNG vehicles should be phased out by 2025.

Starting with the 88 urban nodes of the TEN-T, binding national targets for the electrification of distribution centres and logistics hubs should be introduced for 2025 and 2030. To accelerate the market uptake of regional delivery trucks, the revision should also establish binding targets for the installation of public high-power electric charging stations (HPCCV) at all 88 TEN-T urban nodes by 2025 as well as along the other main nodes and the core network towards the end of the decade. Member States should also be required to deploy and upgrade the electricity grid infrastructure alongside the core network which will be necessary to connect megawatt charging stations for battery electric long-haul trucks. ERS should become a recognised technology in the revised AFID to allow Member States using it to meet their binding targets for the TEN-T core network.

In terms of the deployment of hydrogen refuelling infrastructure for trucks, targets could be set for major European sea ports to leverage the synergy effects with the fuel's future role in maritime shipping and exploit its higher cost-effectiveness by saving on the significant distribution costs.

7.5. Supply of zero-emission trucks

National sales phase-out of ICE trucks by 2035 and 2040

France should adopt a sales ban for ICEVs with a GCW below 26 t for 2035 and above 26 t for 2040. Daimler as the world's biggest truck manufacturer has already announced to end the development of ICEVs and that, from 2039, all trucks sold in the triad markets of Europe, Japan and North America will be ZEVs, i.e. either battery electric or hydrogen.[204] The British National Infrastructure Commission has called for a ban on new diesel-powered HGVs by 2040.[205]

This would require the EU to adopt legislative measures allowing Member States to implement phase-outs in compliance with EU type-approval and internal market rules.[206] The alternative would be to impose a ban on new registrations directly at EU level as part of the upcoming revision of the CO_2 standards for HDVs (see below).

CO_2 standards for HDVs

The EU has recently adopted its first-ever CO_2 emission performance standards for trucks. By the end of 2022, the Commission has to review the Regulation's effectiveness in terms of the ZLEV incentive mechanism, the extension to currently unregulated vehicle types (including trailers and buses) as well as the 2030 reduction target and possible new targets beyond that date. The review needs to take into account the EU's commitments under the Paris Agreement.

There is ample evidence that the demand for zero-emission trucks is growing swiftly, but that manufacturers are struggling to supply the needed production volume to the market over the next years. To overcome this supply gap, France should make the case for an ambitious 2022 review at EU level, thereby sending a strong market signal to truck makers to increase the production and sale of ZEVs. The review should address a number of issues:

- The average fleet reduction target for 2030 needs to be considerably increased beyond the current 30%. The potential for increasing the fuel efficiency of ICEVs in a cost-effective manner has proven to be higher than the current target (see section 3.1.1). More importantly, a noticeable part of the 2030 fleet reduction target will be met by the increasing deployment of ZLEVs, a trend which will continue to intensify in the coming years. Consequently, a revised 2030 target will not require fuel economy improvements to the same extent but would instead be met through a combination of increased fuel efficiency and the accelerating deployment of ZLEVs.
- The standards and VECTO need to be extended to cover the currently unregulated vehicle types (trailers and buses) and vehicle groups (other than 4, 5, 9 and 10) to the largest extent which is practically implementable in the given timeframe.
- The ZLEV incentive mechanism should be replaced by a mandatory sales mandate for 2025 and 2030 which would oblige manufacturers to sell a certain share of ZEVs out of their total fleet sales. The share could vary depending on the vehicle category and weight class. California has proposed such a regulation which would introduce binding sales targets from 2024 onwards and reach a 40% zero-emission sales quota for class 7 and 8 tractors (GCW above 12 t) by 2032.[207]
- The revision should also consider the introduction of an EU-wide sales phase-out for ICEVs for 2035 (below 26 t) and 2040 (above 26 t) to provide legal clarity in terms of EU type-approval and internal market rules and convey a strong market signal that the drivetrain transition is inevitable.

Weights and Dimensions Directive

Since it is not directly applicable, the two-tonne additional maximum weight allowance for ZEVs, which was introduced by the CO_2 standards as an amendment to the Directive, needs to be transposed into French national law. This needs to happen as soon as possible in order to compensate for the currently still higher vehicle weight of battery electric- and hydrogen-powered vehicles compared to ICEVs. The new provision can be included in Article R312-4 of the *Code de la route*.[208]

7.6. Zero-emission urban freight

In terms of air pollution, HGVs are responsible for significant pollutant emissions in urban areas. According to the most recent data available, 22% of NOx and 5% of PM 2.5 road transport emissions in the Greater Paris Area are due to trucks.[209] France has established a sticker labelling system (*Crit'Air*) for urban areas in order to allow cities to impose driving restrictions for polluting vehicles.[210] Despite multiple evidence that gas-powered trucks do not offer meaningful air quality benefits compared to diesel vehicles (see section

3.1.5), they are receiving the Crit'Air certificate 1, the least polluting category after ZEVs.[211] This classification should be changed as soon as possible in view of the poor emissions performance of gas trucks under real-world driving conditions.

In this context, the development of a zero-emission city logistics strategy may be beneficial. The larger French cities should also consider introducing zero-emission zones for commercial vehicles (i.e. vans and trucks) with a view towards 2025 and including transitional arrangements for already registered vehicles until 2030. The Dutch government's agreement to achieve zero-emission city logistics by 2025 with local governments, businesses and research institutions can serve as a blueprint here.[212]

Annex I: Assumptions on conversion efficiencies

Drivetrain and vehicles	Process step	Efficiency rate[xxvi]		Source
		2020	2050	
Direct electrification **BEV and OC-BEV**	Electricity transmission and distribution	94%	95%	Worldbank (2014). Electric power transmission and distribution losses for the European Union. Retrieved from https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS?l&locations=EU
	Charging equipment	95%	95%	Apostolaki-Iosifidou et al. (2017), Measurement of power loss during electric vehicle charging and discharging, Energy, 127, page 737. Retrieved from https://www.sciencedirect.com/science/article/pii/S0360544217303730
	Battery charge efficiency	95%	99%	Peters et al. (2017). The environmental impact of Li-Ion batteries and the role of key parameters – A review. Renewable and Sustainable Energy Reviews. 67. Page 494-495. Retrieved from https://www.sciencedirect.com/science/article/abs/pii/S1364032116304713
	Inversion DC/AC	95%	95%	Larmanie et al. (2012). Electric vehicle technology explained. 2nd edition. Wiley. West Sussex/UK. Page 4-6.
	Engine efficiency	95%	95%	Larmanie et al. (2012).
Compressed hydrogen **FCEV**	Electrolysis[xxvii]	76%	85%	Wachsmuth et al. (2019). Roadmap Gas für die Energiewende – Nachhaltiger Klimabeitrag des Gassektors. Retrieved from https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2019-04-15_cc_12-2019_roadmap-gas_2.pdf, page 82 and 176.

[xxvi] The stated efficiency rates refer to long-haul tractor-trailers. For HGVs of lower weight classes, the rates would remain largely the same except for a slightly lower average brake thermal efficiency (BTE) for ICEVs.
[xxvii] There are efficiency differences between different electrolyser technologies. The rates above reflect values from the cited literature for high-temperature electrolysis. It should be noted that the above estimates are on the optimistic and upper end and reflect a maximum technical potential of high-temperature SOEC technology.

	Transport, storage and distribution incl. compression[xxviii]	89%	89%	Wachsmuth et al. (2019).
	H_2 to electricity conversion	54%	61%	National Research Council (2013). Transitions to Alternative Vehicles and Fuels, The National Academies Press, Washington, DC/US, page 33. Retrieved from https://www.nap.edu/catalog/18264/transitions-to-alternative-vehicles-and-fuels
	Inversion DC/AC	95%	95%	Larmanie et al. (2012).
	Engine efficiency	95%	95%	Larmanie et al. (2012).
Fossil diesel reference and Power-to-liquid **ICEV_diesel and ICEV_PtL**	Electrolysis	76%	85%	Wachsmuth et al. (2019).
	CO_2 direct air-capture and FT-synthesis[xxix]	65%	67%	Heinemann et al. (2018). Die Bedeutung strombasierter Stoffe für den Klimaschutz in Deutschland. Retrieved from https://www.oeko.de/fileadmin/oekodoc/PtX-Hintergrundpapier.pdf, page 22.
	Engine efficiency[xxx]	42%	48%	Delgado et al. (2017). Fuel efficiency technology in European heavy-duty vehicles: Baseline and potential for the 2020-2030 timeframe. Retrieved from https://theicct.org/sites/default/files/publications/EU-HDV-Tech-Potential_ICCT-white-paper_14072017_vF.pdf, page 2 and 12.
Liquefied power-to-methane **ICEV_PtM**[xxxi]	Electrolysis	76%	85%	Wachsmuth et al. (2019).
	CO_2 direct air-capture and methanation	71%	74%	Wachsmuth et al. (2019).

[xxviii] This refers to compressed hydrogen onboard storage. The fuel can also be liquefied and stored onboard in order to reduce volume. However, this would lead to increased storage costs and additional energy consumption due to boil-off losses. Irrespective of this, if the hydrogen is to be imported from outside Europe, it will need to be liquefied for transportation (tanker) and distribution (high-pressure tube trailer) purposes.
[xxix] Literature sources state that 80 to 100% of the required heat demand for the DAC can be provided through waste heat from the FT-synthesis. It is therefore assumed that no additional process heat needs to be supplied. The chosen DAC method is temperature swing adsorption, also called low-temperature DAC.
[xxx] The values indicate the average BTE based on a peak BTE of 45% (2020) and 51% (2050).
[xxxi] This study presumes the dual-fuel CI HPDI technology for ICEVs_PtM with an engine efficiency on par with diesel.

	Transport, storage and distribution incl. liquefaction	93%	93%	Wachsmuth et al. (2019).
	Engine efficiency	42%	48%	Delgado et al. (2017).

Annex II: Cost assumptions

Vehicle costs

Vehicle costs (excl. residual value and VAT)						
Pathway		**2020**	**2025**	**2030**	**2040**	**2050**
ICEV_diesel	Retail price	€ 105,493	€ 110,337	€ 115,261	€ 115,261	€ 115,261
	Maintenance & repairs	€ 17,904 p.a.	€ 18,084 p.a.	€ 18,084 p.a.	€ 18,084 p.a.	€ 18,084 p.a.
	Vehicle taxes	€ 610 p.a.	€ 610 p.a.	€ 610 p.a	€ 610 p.a	€ 610 p.a
BEV	Retail price	€ 319,818	€ 241,403	€ 171,174	€ 171,174	€ 171,174
	Maintenance & repairs	€ 12,600 p.a.	€ 12,600 p.a.	€ 12,600 p.a.	€ 12,600 p.a.	€ 12,600 p.a.
	Vehicle taxes	€ 573 p.a.	€ 573 p.a.	€ 573 p.a.	€ 573 p.a.	€ 573 p.a.
OC-BEV	Retail price	€ 199,551	€ 160,947	€ 126,284	€ 126,284	€ 126,284
	Maintenance & repairs	€ 12,840 p.a.	€ 12,840 p.a.	€ 12,840 p.a	€ 12,840 p.a	€ 12,840 p.a
	Vehicle taxes	€ 573 p.a.	€ 573 p.a.	€ 573 p.a.	€ 573 p.a.	€ 573 p.a.
FCEV	Retail price	€ 182,179	€ 152,966	€ 131,050	€ 131,050	€ 131,050
	Maintenance & repairs	€ 23,100 p.a.	€ 16,440 p.a.	€ 16,440 p.a.	€ 16,440 p.a.	€ 16,440
	Vehicle taxes	€ 573 p.a.	€ 573 p.a.	€ 573 p.a.	€ 573 p.a.	€ 573 p.a.
ICEV_PtL	Retail price	€ 105,493	€ 110,337	€ 115,261	€ 115,261	€ 115,261

	Maintenance & repairs	€ 17,904 p.a.	€ 18,084 p.a.	€ 18,084 p.a.	€ 18,084 p.a.	€ 18,084 p.a.
	Vehicle taxes	€ 610 p.a	€ 610 p.a	€ 610 p.a	€ 610 p.a	€ 610 p.a
ICEV_PtM	Retail price	€ 128,912	€ 122,629	€ 115,261	€ 115,261	€ 115,261
	Maintenance & repairs	€ 19,212 p.a.	€ 17,892 p.a.	€ 17,892 p.a.	€ 17,892 p.a.	€ 17,892 p.a.
	Vehicle taxes	€ 573 p.a.	€ 573 p.a.	€ 573 p.a.	€ 573 p.a.	€ 573 p.a.

Notes: Nominal prices for 2015. All costs are kept constant for 2040 and 2050 as it is not possible to make reasoned assumptions beyond 2030. Retail price includes manufacturing costs due to glider, conventional drivetrain, electric motor, fuel cell system, battery, pantograph and fuel storage system and multiplied with a mark-up factor of 1.4 to determine the net retail price. Maintenance & repairs include costs due to general servicing, urea solution for the exhaust aftertreatment system and the pantograph. Vehicle taxes include registration tax, additional parafiscal charge and special tax on certain motor vehicles. BEV retail price includes opportunity costs due to additional battery weight until 2030. Financing costs are excluded.

Sources: Kühnel et al. (2018), Meszler et al. (2018), BloombergNEF (2019), Element Energy (2019), ACEA (2019).

Battery costs

	2020	2025	2030	2040	2050
Net costs per kWh	€ 135	€ 95	€ 56	€ 56	€ 56
Retail costs per kWh	€ 188	€ 133	€ 78	€ 78	€ 78
Energy density of the battery pack	183 Wh/kg	245 Wh/kg	318 Wh/kg	478 Wh/kg	508 Wh/kg

Notes: Nominal prices for 2019. Costs are kept constant beyond 2030. The retail cost includes the same mark-up factor of 1.4 as for the vehicle costs to determine the net retail price after manufacturing and distribution costs. The battery pack density values are the low assumptions on the potential for future improvement.

Sources: BloombergNEF (2019), Kühnel et al. (2018), Ricardo Energy & Environment (2019).

Fuel consumption

HGV Pathway (40/44 t GCW)	in kWh/km					in $litre_{diesel}$/100 km				
	2020	2025	2030	2040	2050	2020	2025	2030	2040	2050
ICEV_diesel	3.29	2.82	2.34	2.34	2.34	33.06	28.27	23.47	23.47	23.47
BEV (battery-to-wheel)	1.43	1.36	1.29	1.29	1.29	14.36	13.65	12.95	12.95	12.95
BEV (from the grid)	1.57	1.50	1.42	1.42	1.42	15.80	15.03	14.26	14.26	14.26
OC-BEV (battery-to-wheel)	1.53	1.45	1.38	1.38	1.38	15.33	14.59	13.85	13.85	13.85
OC-BEV (from the grid)	1.68	1.59	1.51	1.51	1.51	16.83	16.00	15.16	15.16	15.16
FCEV	2.51	2.30	2.09	2.09	2.09	25.20	23.09	20.98	20.98	20.98
ICEV_PtL	3.29	2.82	2.34	2.34	2.34	33.06	28.27	23.47	23.47	23.47
ICEV_PtM	3.29	2.82	2.34	2.34	2.34	33.06	28.27	23.47	23.47	23.47

Notes: The values describe the vehicle's final energy consumption. Values beyond 2030 are kept constant. Taking into account fuel efficiency improvement of ICEVs of 29% by 2030. For OC-BEVs, above values represent the fuel consumption when drawing traction from the overhead lines; when running on the battery, the BEV values apply.

Sources: Authors' calculations, Kühnel et al. (2018), Delgado et al. (2017), Moultak et al. (2017).

Fuel costs

North Sea scenario						
Pathway		€-cent/kWh				
		2020	2025	2030	2040	2050
Fossil diesel reference	Total[xxxii]	6.36	6.36	6.95	7.65	8.34
	Total incl. taxes &	10.74	10.74	11.34	12.03	12.72

[xxxii] The diesel prices are as of February 2020.

	levies[xxxiii]					
Electricity	LCOE	9.22	7.80	7.23	6.14	5.11
	Transport to FR	no additional cost				
	Distribution in FR	4.40	4.40	4.40	4.40	4.20
	Total	13.62	12.20	11.63	10.54	9.51
	Total incl. taxes & levies	17.25	15.83	15.26	14.17	13.14
	at reduced CSPE rate	15.05	13.63	13.06	11.97	10.94
Hydrogen	Production	14.81	12.60	11.49	9.48	7.72
	Liquefaction	6.10	5.65	5.20	4.70	4.10
	Transport to FR	no additional cost				
	Distribution in FR	2.40	2.40	2.40	2.40	2.40
	Total	23.31	20.65	19.09	16.58	14.22
	Total incl. taxes & levies[xxxiv]	23.31	20.65	19.09	16.58	14.22
Power-to-liquid	Production	26.11	23.07	20.62	17.76	15.25
	Liquefaction	-				
	Transport to FR	no additional cost				
	Distribution in FR	1.00	1.00	1.00	1.00	1.00
	Total	27.11	24.07	21.62	18.76	16.25
	Total incl. taxes & levies[xxxv]	31.50	28.46	26.00	23.15	20.64
Power-to-	Production	25.82	22.73	20.33	17.44	15.52

[xxxiii] The values include the diesel fuel rebate.
[xxxiv] There is currently no excise duty on hydrogen.
[xxxv] The values include the diesel fuel rebate.

methane	Liquefaction	0.69	0.68	0.67	0.64	0.61
	Transport to FR	no additional cost				
	Distribution in FR	1.10	1.10	1.10	1.10	1.10
	Total	27.61	24.51	22.10	19.18	17.23
	Total incl. taxes & levies	28.13	25.03	22.62	19.70	17.75

Notes: Nominal prices for 2017 excl. VAT. Renewable electricity production from offshore wind in the North Sea according to the reference scenario in the Agora PtG/PtL calculator. LCOE includes grid connection fees. Electricity network distribution costs in FR refer to TURPE. LCOE, high-temperature SOEC electrolysis, FT-synthesis and Sabatier process based on 4,000 full-load hours. Fossil diesel costs for 2020 and 2025 are based on the February 2020 market price in France and projections for the following years from the reference scenario in the Agora PtG/PtL calculator. Taxes & levies refer to TICPE, TICGN, Coûts de commercialisation, CSPE, TCFE and CTA. For hydrogen, the current tax exemption is maintained, as is the currently extremely low excise duty rate on methane used as transport propellant.

Sources: Authors' calculations, Frontier Economics (2018), Kühnel et al. (2018), Mottschall et al. (2019), Ministère de la Transition écologique et solidaire (2020), Observatoire de l'industrie électrique (2019), Energie-Info (2020), European Commission (2011), Weekly Oil Bulletin (2020).

North Africa scenario						
Pathway		**€-cent/kWh**				
		2020	**2025**	**2030**	**2040**	**2050**
Fossil diesel reference	Total[xxxvi]	6.36	6.36	6.95	7.65	8.34
	Total incl. taxes & levies[xxxvii]	10.74	10.74	11.34	12.03	12.72
Electricity	LCOE[xxxviii]	9.22	7.80	7.23	6.14	5.11
	Transport to FR	no additional cost				
	Distribution in FR	4.40	4.40	4.40	4.40	4.40
	Total	13.62	12.20	11.63	10.54	9.51

[xxxvi] The diesel prices are as of February 2020.
[xxxvii] The values include the diesel fuel rebate.
[xxxviii] Under the North Africa scenario, the electricity costs for the electricity pathway remain the same as for the North Sea scenario.

	Total incl. taxes & levies	17.25	15.83	15.26	14.17	13.14
	at reduced CSPE rate	15.05	13.63	13.06	11.97	10.94
Hydrogen	Production	10.16	9.08	8.18	6.65	5.49
	Liquefaction	6.10	5.65	5.20	4.70	4.10
	Transport to FR	0.41	0.41	0.41	0.41	0.41
	Distribution in FR	2.40	2.40	2.40	2.40	2.40
	Total	19.07	17.54	16.19	14.16	12.40
	Total incl. taxes & levies[xxxix]	19.07	17.54	16.19	14.16	12.40
Power-to-liquid	Production	19.89	18.35	16.18	13.97	12.28
	Liquefaction	-				
	Transport to FR	0.01	0.01	0.01	0.01	0.01
	Distribution in FR	1.00	1.00	1.00	1.00	1.00
	Total	20.89	19.36	17.18	14.97	13.28
	Total incl. taxes & levies[xl]	25.28	23.75	21.57	19.36	17.67
Power-to-methane	Production	19.93	18.30	16.18	13.91	12.78
	Liquefaction	0.69	0.68	0.67	0.64	0.61
	Transport to FR	0.03	0.03	0.03	0.03	0.03
	Distribution in FR	1.10	1.10	1.10	1.10	1.10
	Total	21.74	20.10	17.97	15.67	14.51
	Total incl. taxes & levies	22.27	20.62	18.50	16.20	15.04

[xxxix] There is currently no excise duty on hydrogen.
[xl] The values include the diesel fuel rebate.

Notes: Nominal prices for 2017 excl. VAT. Renewable electricity production from offshore wind in the North Sea and renewable electricity production from solar PV in North Africa for synthetic electrofuels according to the reference scenario in the Agora PtG/PtL calculator. LCOE includes grid connection fees. Electricity network distribution costs in FR refer to TURPE. LCOE and high-temperature SOEC electrolysis based on 2,344 full-load hours, FT-synthesis and Sabatier process based on 4,000 full-load hours. Fossil diesel costs for 2020 and 2025 are based on the February 2020 market price in France and projections for the following years from the reference scenario in the Agora PtG/PtL calculator. Taxes & levies refer to TICPE, TICGN, Coûts de commercialisation, CSPE, TCFE and CTA. For hydrogen, the current tax exemption is maintained, as is the currently extremely low excise duty rate on methane used as transport propellant.

Sources: Authors' calculations, Frontier Economics (2018), Kühnel et al. (2018), Mottschall et al. (2019), Pfennig et al. (2017), Ministère de la Transition écologique et solidaire (2020), Observatoire de l'industrie électrique (2019), Energie-Info (2020), Weekly Oil Bulletin (2020).

Infrastructure costs

Charging infrastructure for BEVs		
Specifications of a mega charger (1.2 MW)	Number of chargers per vehicle	0.0075
	Charging time	30 minutes for 400 km range
	Supplied vehicles per day	20
	Service life	15 years
	Capital expenditure	€ 420,000
	Operational expenses per year	€ 4,200 p.a.
Specifications of an overnight charger (150 kW)	Number of chargers per vehicle	1.1
	Charging time	8 hours for 800 km range
	Supplied vehicles per day	0.91
	Service life	15 years
	Capital expenditure	€ 80,000
	Operational expenses per year	€ 800 p.a.
Total infrastructure costs per	Full utilisation	€ 6,988 p.a.

vehicle per year	Half utilisation	€ 13,976 p.a.

Charging infrastructure for OC-BEVs		
Specifications of an overhead catenary system	System voltage	1,500 V_{DC}
	Maximum power consumption per vehicle for traction and battery charging	240 kW
	Average vehicle speed	80 km/h
	Installed permanent power per direction	2 MW/km
	Installed permanent substation power	4 MW/km
	Number of supplied vehicles per direction (at 240 kW)	8 vehicles/km
	Number of supplied vehicles per direction at overload capacity (for up to 2 hrs at 240 kW)	12 vehicles/km
	Possible time gap between vehicles	5.40 seconds
	Possible time gap at overload capacity	4.05 seconds
	Service life	20 years
	Capital expenditure per km (both directions)	€ 3.05 million
	Capital expenditure per MW (both directions)	€ 762,500
	Operational expenses per year	€ 61,000 p.a.
Total infrastructure costs per vehicle per year	Full utilisation	€ 5,338 p.a.
	Half utilisation	€ 10,675 p.a.

Refuelling infrastructure for FCEVs		
Specifications of a hydrogen	Total refuelling capacity	5,468 kg_{H2}

refuelling station	Mean refuelling quantity per vehicle	33 kg_{H2}
	Supplied vehicles per day	110
	Service life	15 years
	Capital expenditure	€ 6.3 million
	Operational expenses per year	€ 63,000 p.a.
Total infrastructure costs per vehicle per year	Full utilisation	€ 4,391 p.a.
	Half utilisation	€ 8,782 p.a.

Refuelling infrastructure for ICEVs_PtM		
Specifications of an LNG refuelling station	Total refuelling capacity	17,000 kg_{LNG}
	Mean refuelling quantity per vehicle	103 kg_{LNG}
	Supplied vehicles per day	83
	Service life	15 years
	Capital expenditure	€ 1.034 million
	Operational expenses per year	€ 27,080 p.a.
Total infrastructure costs per vehicle per year	Full utilisation	€ 1,157 p.a.
	Half utilisation	€ 2,314 p.a.

Notes: Nominal prices for 2015. Infrastructure costs are kept constant throughout the years. ICEVs_diesel and ICEVs_PtL can use the already established refuelling infrastructure. For the sake of simplicity, it is assumed that the investment costs of these petrol stations are already written off and the infrastructure does not need to be replaced after the end of its service life.

Sources: Authors' calculations, Kühnel et al. (2018).

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