

Louvain School of Management

For heavy-duty trucks, which alternative energy carrier between an electric battery and hydrogen leads to a better environmental performance, from a Well-to-Wheels perspective and in the Belgian context?

Author(s): Manon Schoevaerdt
Supervisor(s): Sabine Denis
Academic year 2020.-2021.
Dissertation for the master of Business Engineering (120 ECTS)
Master subject and focus Corporate Sustainable Management
Daytime schedule

Acknowledgement

I would like to thank my supervisor, Sabine Denis, for allowing me to pick a topic that truly fascinated me and for supporting my ideas by providing me with valuable feedback.

I would like to show my gratitude to Stefanie Vandamme and Robin Lataire, from Colruyt Group, for their precious time during our meetings and for guiding me through this challenging task. I would also like to thank them for reviewing the paper and for providing me with insightful comments.

Thank you also to my father, Olivier Schoevaerds, and his friend, Serge Vanhalme, for the interesting discussions that helped me to build a critical point of view on the case. Their interest to the subject was highly motivating.

Finally, I would like to thank the ICHEC Brussels Management School and the Louvain School of Management for the quality education they have provided me.

Table of Contents

1.	Introduction	1
1.1.	Goal, scope and expected contribution	3
1.2.	Structure	3
1.3.	Definitions of concepts	4
1.4.	Glossary	8
2.	Methodology	9
2.1.	Literature review	9
2.2.	Case study	10
2.2.1.	Pathways	11
2.2.2.	WTW integration and calculations	15
3.	Literature review	17
3.1.	The role of heavy-duty vehicles in the energy transition	17
3.1.1.	The transportation sector	17
3.1.2.	Heavy-duty vehicles: Environmental, social, and economic impact	18
3.1.3.	Supply chains: companies' responsibilities	19
3.1.4.	Impactful emission reduction levers for heavy-duty vehicles	22
3.1.5.	Potential alternative fuels and powertrains	24
3.2.	Well-to-Wheels analysis of fuels and energy carriers for heavy-duty vehicles	27
3.2.1.	Well-to-Wheels analysis	28
3.2.2.	Diesel	30
3.2.2.1.	WTT: From primary energy resource to fuel	31
3.2.2.2.	TTW: Powertrain	32
3.2.2.3.	WTW: Environmental performance	32
3.2.3.	Electricity	33
3.2.3.1.	WTT: From primary energy resource to fuel	34
3.2.3.2.	TTW: Powertrain	42
3.2.3.3.	WTW: Environmental performance	43
3.2.4.	Hydrogen	44
3.2.4.1.	WTT: From primary energy resource to fuel	45
3.2.4.2.	TTW: Powertrain	48
3.2.4.3.	WTW: Environmental performance	49
3.3.	Comparison of the environmental performance between Diesel ICEV, BEV, FCEV	50
3.3.1.	Energy efficiency	50
3.3.2.	GHG emissions	52
4.	Results	56

4.1.	General observations	56
4.2.	Nuclear	58
4.3.	Wind	59
4.4.	Natural gas	59
4.5.	EU mix	60
	2016	60
	2030	60
4.6.	Cumulative results	61
4.7.	Sensitivity analysis: BE mix.....	62
	2020	65
	2030	65
5.	Discussion.....	66
5.1.	Results discussion	66
5.2.	Further discussion	67
5.3.	Limits and further research.....	70
6.	Conclusion.....	71
7.	Bibliography	74
8.	Appendices.....	83
	Appendix A: Investigated production pathways for diesel, electricity, and hydrogen.....	83

1. Introduction

Sae Hoon Kim, vice president of Hyundai's fuel cell centre, has stated that "human-caused climate change dictates the end of diesel trucks" (Hirsch, 2019). Indeed, the current road freight transportation is on the verge of a drastic transformation.

The Intergovernmental Panel on Climate Change (2018) warns that global net anthropogenic CO₂ emissions must halve by 2030¹ and reach net zero by 2050, to limit severe environmental impacts. The transportation sector² is one of the biggest source of greenhouse gas (GHG) emissions worldwide (IEA & OECD, 2017), yet remains especially challenging to mitigate. It will demand structural shifts to move people and freight, a shift to low-carbon fuels and improvements in energy efficiencies through technology advancement. Particularly transforming the "road" transport will play a crucial role to reach climate targets, as it is the largest contributor to transport emissions (EEA, 2020). In 2019, the heavy-duty vehicles in Europe were responsible for about a quarter of road transport CO₂ emissions and represented 6% of total European CO₂ emissions (European Commission, 2019). The activity of heavy-duty vehicles will keep increasing along with emissions, due to the growing economic activity, international trade and expansion of e-commerce; urging the call for action (IEA, 2020a).

Until now, regulations to cut down greenhouse gas emissions and curb air pollution, have targeted passenger vehicles more than heavy-duty vehicles, although these represent the major share of oil demand and CO₂ emissions. Standards to limit CO₂ emission are slowly coming into force for heavy-duty vehicles. (IEA, 2020a) But political actions are not sufficient, and companies need to take the lead to embrace the sustainability path. To prepare for the transition, companies need to adapt their strategy now, to become resilient for future disruptions.

Heavy-duty vehicles play a critical role in the supply chain of organisations, by delivering all types of goods from the production points to the manufacturing sites and to their final selling point. To reduce the environmental impact of supply chains, all emission reduction levers need to be activated. An impactful reduction lever is the use of alternative fuels and powertrains for heavy-duty vehicles. But which alternative should be chosen amongst

¹ From 2010 levels. (IPCC, 2018)

² The transportation sector includes road, maritime, rail, and air transport. (IEA & OECD, 2017)

biofuels, natural gas, electricity, and hydrogen? It seems that battery electric trucks and hydrogen fuel cell electric trucks are the most promising substitutes until now. They present a higher potential, than biofuels and natural gas, for deep decarbonisation of the transport sector in the long term. Additionally, the electrified powertrains result in zero tailpipe emissions, greatly contributing to the reduction of local greenhouse gas emissions and air pollutants. However, depending on the primary resources used upstream in the production pathway, the global emissions vary greatly. This leads to the research question of the thesis: *“For heavy-duty trucks, which alternative energy carrier between an electric battery and hydrogen leads to a better environmental performance, from a Well-to-Wheels perspective and in the Belgian context?”*

This paper evaluates the environmental performance only in terms of “energy efficiency” and “greenhouse gas emissions”, for battery electric trucks and hydrogen fuel cell electric trucks. Both are also being compared to conventional diesel trucks, to assess their potential to deeply reduce emissions. The environmental performance is based on a Well-to-Wheels analysis. This analysis includes stages of the fuel life cycle, from the extraction of the primary energy source until the consumption of the final fuel in the vehicle. The Well-to-Wheels differs from a Life Cycle Analysis, as it does not take into account energy and emissions related to building facilities and the vehicles, or end of life aspects. As such, this study considers energy expenditures and greenhouse gas emissions involved during production, transportation, manufacturing, distribution, and consumption of the fuel in the vehicle. To find out which solution leads to the best environmental performance, upstream and tailpipe emissions need to be considered, as both the choice of primary energy source and powertrain efficiency can strongly influence results.

Hydrogen appears as being an energy superstar, supporting the clean energy transition. Will hydrogen technology play a key role in the decarbonisation of road freight transport? Do hydrogen powered trucks lead to a lower carbon footprint than battery electric trucks?

Since electricity and hydrogen can be produced from many different primary energy sources, such as nuclear power, renewable energies, or natural gas, it is necessary to assess which pathways require less energy and produce less greenhouse gas emissions. This brings to the question whether the use of the energy carriers leads to any advantage, if the primary source

is not carbon-neutral? Can carbon capture technology compensate for emissions from fossil-based hydrogen?

While the environmental aspect cannot be neglected anymore, when companies decide to switch from diesel conventional trucks to electrified trucks, the trade-offs cannot be based solely on the carbon footprint. Indeed, other aspects will need to be considered such as the operating range, recharging/ refuelling time, payload restrictions, available infrastructure, and costs.

1.1. Goal, scope and expected contribution

The aim of the research is, according to available primary energy resources, to assess which alternative energy carrier would have the best environmental performance in the future to substitute the conventional fuel, diesel, for long-haul heavy-duty trucks in the European and Belgian context. Therefore, a case study has been conducted in collaboration with engineers of the R&D department of Colruyt. The model is based on a typical use case for a big retailer, with data retrieved from the “JEC³ Well-to-Wheels report v5”. The report, published by the Joint Research Centre in 2020, provides the most recent, comprehensive, and transparent compilation of WTW studies for heavy-duty trucks in the European context.

This research is thus providing the most up-to-date comparative study of the battery electric trucks, hydrogen fuel cell electric trucks and conventional diesel trucks for long-haul missions, in the Belgian context. Unlike other research, it also provides a forecast of environmental performances for 2025+, considering future technologies and gain in efficiencies. It also includes a large panel of production pathways for electricity and hydrogen, allowing to understand where it should be sourced from. Consequently, the findings can support companies, willing to switch to low-carbon fuels, to understand the environmental impact of each solution.

1.2. Structure

The first part consists of the literature review which provides the necessary knowledge to understand the case study. The first chapter of the literature review provides the current context for the transportation sector and the environmental, social, and economic impact of heavy-duty vehicles. To understand the companies’ responsibilities in this transition, the link

³ JCR, EUCAR, Concawe

between heavy-duty vehicles and companies' supply chain emissions is discussed. Then, the different levers to reduce the impact of heavy-duty vehicles are reviewed, bringing forward the solution of switching to alternative fuels and powertrains. The different potential alternatives are exposed and afterwards the choice of analysing electrified powertrains is argued. The second chapter of the literature review provides the necessary background to understand the whole production pathways of diesel, electricity, and hydrogen from "well" to "wheels". The exact meaning and reason behind a Well-to-Wheels analysis are presented. The chapter is then broken down according to each final fuel, diesel, electricity, and hydrogen, to review their respective Well-to-Wheels pathways. It allows the reader to identify where energy consumption and greenhouse gas emissions occur in the process. The chapter is concluded with the comparison of results between different Well-to-Wheels research in the literature. The second part of the work is a case study, providing the actual environmental performance of diesel, battery electric, and hydrogen trucks⁴, from a Well-to-Wheels perspective. Different pathways are analysed according to available primary resources in Europe and Belgium. The results illustrate the energy consumption and greenhouse gas emissions for each final fuel. Finally, the results are interpreted and further discussed, along with the limits and recommendation for further research.

1.3. Definition of concepts

Air pollutants

Air pollutants are substances causing air pollution which harms the human health and environment. These air pollutants can be either synthetic (man-made) or natural (e.g., wildfires). The EPA has identified six pollutants : carbon monoxide (CO), nitrogen oxides (NO_x), sulphur oxides (SO_x), particle pollution (often referred to as particulate matter (PM)), lead, and ground-level ozone.(National Centre for Environmental Health, 2021)

Battery Electric Vehicle

"Battery Electric Vehicles (BEV) are the simplest type of EV from a conceptual perspective, using electrical power from a single source—the electrochemical battery—to power one or more electric motors. Typically, a single electric motor is connected to the front axle through a simple one- or two-speed gearbox, but there are several other possible variations in the

⁴ The heavy-duty vehicle configuration analysed is the semi-trailer tractor, with 40 tons gross vehicle mass rating and 14.290 tons in weighted payload, designed for long-haul missions.

driveline architectures. One significant variation is to use a series of four “hub motors” attached to each wheel rather than a single drive motor.”(Delucchi & Lipman, 2010, Chapter 2)

Carbon Capture and Storage

“Carbon capture and storage (CCS) is the process of capturing and storing carbon dioxide (CO₂) before it is released into the atmosphere. The technology can capture up to 90% of CO₂ released by burning fossil fuels for the generation of electricity and industrial processes such as cement production.”(The London School of Economics and Political Science, 2018)

CO_{2eq}

“Carbon dioxide equivalent (CO_{2eq}) stands for a unit based on the global warming potential (GWP) of different greenhouse gases. The CO_{2eq} unit measures the environmental impact of one tonne of these greenhouse gases in comparison to the impact of one tonne of CO₂.”(Climate Policy Info Hub, n.d.)

Energy carrier

“An energy carrier is a substance (fuel) or sometimes a phenomenon (energy system) that contains energy that can be later converted to other forms such as mechanical work or heat or to operate chemical or physical processes.” (ISO 13600, 1997) Such carriers include electric batteries and hydrogen. “Energy carriers vary on multiple dimensions (e.g. volumetric energy density, gravimetric energy density, ease of storage, ease of transport, cleanliness) and they are only partially substitutable (e.g. try running a truck on battery-stored electricity).”(Sorrell, 2015, p. 77) Although electricity and hydrogen are referred to as fuels they should primarily be considered as energy carriers.

Energy density

“Energy density is the amount of energy that can be stored in a given mass of a substance or system. The higher the energy density of a system or material, the greater the amount of energy stored in its mass. A material can release energy in four types of reactions. These reactions are nuclear, chemical, electrochemical, and electrical. Energy density can be expressed in two ways :” (University of Calgary, n.d.)

- **“Volumetric energy density** - how much energy a system contains in comparison to its volume; typically expressed in Megajoules per litre (MJ/L) or

- **Gravimetric energy density** - how much energy a system contains in comparison to its mass; typically expressed in Megajoules per kilogram (MJ/kg).” (University of Calgary, n.d.)

Energy efficiency

“Energy efficiency links the energy output to the energy input, meaning that a system is more energy efficient than another system if it delivers the same service for less energy input. Common examples for energy efficient devices are energy-saving light bulbs that produce the same amount of light as conventional light bulbs but use less energy.”(Climate Policy Info Hub, n.d.)

Fuel Cell Electric Vehicle

“FCEV stands for Fuel Cell Electric Vehicle. FCEVs are a type of vehicle that use compressed hydrogen gas as fuel to generate electric power via a highly efficient energy converter, a fuel cell. The fuel cell transforms the hydrogen directly into electricity to power an electric engine.”(Hydrogen Mobility Europe, 2015) As such, the fuel cell is an electricity-generating device. “The fuel cell principle is the opposite of electrolysis since it is based on the oxidation of a fuel and the reduction of an oxidant, resulting in the simultaneous production of electrical energy, water and heat.”(Solar Impulse, 2021)

Greenhouse Gas emissions

Greenhouse gases are “gases in the atmosphere that absorb and emit radiation within the thermal infrared range.” (Climate Policy Info Hub, n.d.) “Greenhouse gases refer to the sum of seven gases that have direct effects on climate change: carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF₆) and nitrogen trifluoride (NF₃).”(OECD, n.d.)

Heavy-duty truck

“Heavy-duty trucks are commercial vehicles with a gross vehicle weight greater than 15 tonnes. They typically serve long-haul delivery of goods. The heaviest heavy-duty trucks are operated essentially year-round, often covering more than 100 000 kilometres per year and in some instances twice this distance. They account for the majority (about 70%) of road freight activity.”(IEA & OECD, 2017)

Heavy-duty vehicle

“Heavy-duty vehicles are defined as commercial vehicles and buses with a gross vehicle weight greater than 3,5 tonnes.”(ICCT, n.d.)

JEC

“JEC is a collaboration between the JCR (European commission’s Joint Research Centre), EUCAR (the European Council for Automotive Research and development) and Concawe (the European oil companies’ association for environment, health and safety in refining & distribution).”(European Commission, 2016)

Long-haul

“The long-haul duty cycle involves multi-day intercity travel with maximum daily trip lengths of up to 800 km if the vehicle is equipped with one driver. The trip length is aligned with EU rules on driving times and rest periods which foresee maximum daily driving periods of 9 hours (which can go up to 10 hours). At an 80 km/h average vehicle speed, this amounts to 800 km per day. The average annual mileage is set at 120,000 km also based on the European Commission. (Transport & Environment, 2020)

Lower heating value

“The lower heating value (also known as net calorific value) of a fuel is defined as the amount of heat released by combusting a specified quantity of fuel (initially at 25°C) and returning the temperature of the combustion products to 150°C, which assumes the latent heat of vaporization of water in the reaction products is not recovered.”(Hydrogen Tools, n.d.) It is used to calculate the energy content of a fuel.

Powertrain

“In a motor vehicle, the powertrain consists of the source of propulsion (e.g. the engine or electric motor) and the drivetrain system which transfers this energy into forward movement of the vehicle.” (Röck et al., 2020)

Well-to-Wheels

A Well-to-Wheels (WTW) analysis is used to determine the environmental impact of a fuel in terms of greenhouse gas emissions (GHG) and energy efficiency. The WTW analysis can be divided in two parts, the **Well-to-Tank (WTT)** and **Tank-to-Wheels (TTW)**. The WTT considers energy expenditures and GHG emissions coming from the extraction of the primary energy

source until final distribution to end user. Thus, this includes the production, transport, manufacturing, and distribution of road fuels. While the TTW accounts for energy expended and GHG emissions from burning fuel in the vehicle, or in other words, the tailpipe emissions.(European Commission, 2016)

1.4. Glossary

BEV	Battery Electric Vehicle(s)
CCGT	Combined-Cycle Gas Turbine
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
FCEV	Fuel Cell Electric Vehicle(s)
GHG	Greenhouse Gas
GWP	Global Warming Potential
HDV	Heavy-duty vehicle(s)
HV	High Voltage
ICE CI	Internal Combustion Engine Compressed Ignition
ICEV	Internal Combustion Engine Vehicle
JEC	JCR, EUCAR, Concawe
LHV	Lower Heating Value
LNG	Liquified Natural Gas
LV	Low Voltage
MV	Medium Voltage
PEM	Proton Exchange Membranes
PMSM	Permanent Magnet Synchronous Motor
SMR	Steam Methane Reforming
TTW	Tank-to-Wheels
WTT	Well-to-Tank
WTW	Well-to-Wheels

2. Methodology

2.1. Literature review

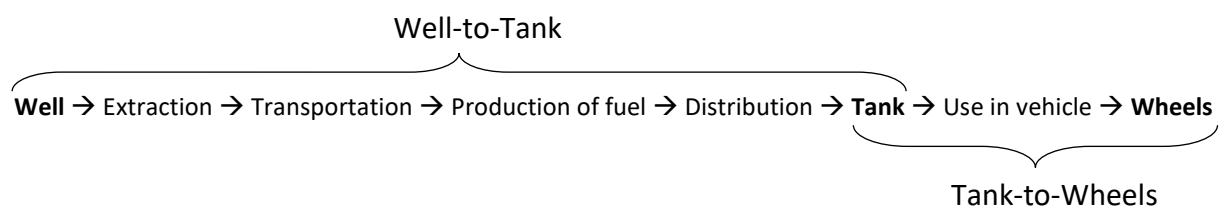
For the first chapter of the literature review, the method of a “funnel” has been applied. It starts with the broader context and is gradually narrowed to the topic of this thesis. Indeed, to understand why this research focuses on electric batteries and hydrogen as alternative energy carriers, first a global picture was necessary. Firstly, the transport sector is identified as one of the biggest contributors to global GHG emissions. This is narrowed down to the “road” transportation which accounts for the majority of emissions in the transportation sector. Road transport is refined to the heavy-duty vehicles and their impact. The choice of targeting heavy-duty vehicles was made, because their activity along with their emissions keep growing and they can be directly related to the activity of companies. It is demonstrated that companies are accountable for direct and indirect GHG emissions, including the emissions from transportation of goods, which requires heavy-duty vehicles. The focus is then placed on how to reduce the carbon footprint of heavy-duty vehicles. The use of alternative fuels and powertrains is identified as the most impactful emission reduction lever. Finally, amongst the alternatives, battery electric trucks and hydrogen powered trucks stand out. The development of ideas was mainly build upon the revision of reports published by big institutions such as, the International Energy Agency (IEA), the European Environment Agency (EEA), the European Commission, etc. It helped to lay the foundation before getting to the heart of the matter.

The second chapter of the literature is the collection of information and data, required to build the case study. The structure is organised according to each fuel, to be able to break down their production pathways and identify where energy consumption and GHG emissions occur. Here, scientific journal articles were gathered and compared. Searches were carried out on several databases, including Discovery of the UCLouvain, Google Scholar, Cairn, ScienceDirect, and ResearchGate. Articles were searched with the key words “well-to-wheels”, “heavy-duty trucks”, “battery electric vehicle”, “hydrogen fuel cell electric vehicle”, and “environmental performance”. Articles were selected based on the relevance of their scope. Finally, the results of different articles were compared to identify main trends and findings to, later, confront them with the results from the case study.

2.2. Case study

To compare the environmental performance of battery electric trucks, hydrogen powered trucks and conventional diesel trucks, a Well-to-Wheels (WTW) analysis was conducted. This was done by collecting data about the energy consumption and GHG emissions for the Well-to-Tank (WTT) and Tank-to-Wheels (TTW) (Figure 1). The WTT includes extraction and transportation of primary resources followed by the production and distribution of the final fuel. The TTW is the use of the final fuel in the truck.

Figure 1: Graphic representation of stages accounted in a Well-to-Wheels analysis



Contact with the R&D department of Colruyt was established to review the road freight transportation in Belgium and analyse a typical use case for big retailers. Engineers from Colruyt have provided the necessary information and guidelines to build the case study. To do so, they indicated reports from the JEC as basis of my research. Consequently, the data and calculations are based on JEC WTT report v5 (2020b), JEC TTW report v5 (2020), and JEC WTW report v5 (2020) since they provide the most comprehensive, transparent, and recent compilation of WTW data for HDV in the European context. The WTW analysis is thus based on the European market, with 2016 as base year and 2025+ forecast is included, to consider new technologies and improvement of efficiencies in the future. The JEC report offers a large range of fuels production pathways. Since electricity and hydrogen can be produced from multiple primary sources, Colruyt's engineers indicated the most relevant production pathways that needed to be study. For electricity and hydrogen, the primary sources considered are nuclear, wind and natural gas as well as the average EU electricity mix pathway. The primary source for diesel is crude oil, the traditional pathway is analysed. For each pathway, the WTW energy expended and WTW GHG emitted were calculated. Finally, for the sensitivity analysis, the electricity mix has been adapted to the Belgian electricity mix in 2020 and a prediction for 2030. The nuclear, wind and natural gas results were combined, proportionally to their share in the Belgian electricity mix. The 2020 As such, it assesses the potential of alternative energy carriers when the Belgian electricity mix is considered.

The aim of the case study is, according to available primary energy sources and corresponding production pathways, to assess which alternative fuel has the best environmental⁵ performance compared to a conventional fuel, from a WTW perspective. Therefore, in the scope of this case, diesel, electricity, and hydrogen have been considered in combination with their respective powertrains ICE, BEV, and FCEV.

The final WTW results have first been discussed with Hervé Jeanmart (Expert in hydrogen) and Serge Vanhalme (Mechanical-Electrical Civil Engineer) to be further improved. Finally, they have been reviewed and confirmed by Colruyt's Engineers. The interpretation of results in chapter 4, are organised by primary energy source, in order to visualize which solution is the best according to the available resource. The WTW results are illustrated through graphics to facilitate the comparison of the environmental performance of each truck and its respective fuel pathways.

2.2.1. Pathways

Well-to-Tank

The variable that determines the **WTT** assessment is the production pathway of the fuel according to a chosen primary energy source. It is important to underline that, a fuel/ energy carrier must be produced from a form of primary energy, which can either be contained in a fossil raw material or fossil fuel, or derived from renewable sources (i.e., wind power). Since electricity and hydrogen can be produced from several different primary energy sources, the most relevant pathways were selected and investigated. Selection was based on Colruyt's advice and the literature review. Sixteen pathways are considered, to convert primary energy source into the final fuels. Graphic representations to better visualize each pathway have been created (Appendix A). The investigated pathways are listed below. A name is given to each pathway, as reference to its powertrain and primary source or fuel, and will be used for the graphics later:

- a. **(ICEV) Diesel:** Crude oil from typical EU supply → transport by sea → refining in EU (marginal **diesel** production) → typical EU distribution and retail
- b. **(BEV) Nuclear:** Nuclear fuel (uranium) provision → nuclear power plant (**electricity** generation) → Low Voltage grid

⁵ Here only the energy consumption and GHG emissions are considered

- c. **(FCEV) Nuclear:** Nuclear fuel (uranium) provision → nuclear power plant (electricity generation) → on-site electrolyser (hydrogen production) + compression
- d. **(BEV) Wind:** Wind → Wind turbines (on/offshore) (electricity generation) → Low Voltage grid
- e. **(FCEV) Wind:** Wind → Wind turbines (offshore) (electricity generation) + central electrolyser (“green” hydrogen production) → distribution by pipeline (50km) + compression
- f. **(BEV) LNG:** Remote NG → liquefaction → shipping LNG → CCGT (electricity generation) → Low Voltage grid
- g. **(FCEV) LNG:** Remote NG → liquefaction → shipping LNG → CCGT (electricity generation) → on-site electrolyser (hydrogen production) + compression
- h. **(BEV) piped NG:** Piped NG → pipeline into Europe (4000km) → CCGT (electricity generation) → Low Voltage grid
- i. **(FCEV) piped NG:** Piped NG → pipeline into Europe (4000km) → CCGT (electricity generation) → on-site electrolyser (hydrogen production) + compression
- j. **(FCEV) SMR:** Piped NG → pipeline into Europe (4000km) → Steam Methane Reforming (“grey” hydrogen production) → pipeline (50km) + compression
- k. **(FCEV) SMR + CCS:** Piped NG → pipeline into Europe (4000km) → Steam Methane Reforming + Carbon Capture (“blue” hydrogen production) → pipeline (50km) + compression
- l. **(BEV) EU mix 2016:** EU primary resource mix → EU electricity mix 2016 → Medium Voltage grid
- m. **(BEV) EU mix 2030:** EU primary resource mix → EU electricity mix 2030 → Medium Voltage grid
- n. **(FCEV) EU mix 2016 MV:** EU primary resource mix → EU electricity mix 2016 → Medium Voltage grid → on-site electrolyser (hydrogen production) + compression
- o. **(FCEV) EU mix 2030 MV:** EU primary resource mix → EU electricity mix 2030 → Medium Voltage grid → on-site electrolyser (hydrogen production) + compression
- p. **(FCEV) EU mix 2016 HV:** EU primary resource mix → EU electricity mix 2016 → High Voltage grid + central electrolyser (hydrogen production) → pipelines (50km) + compression

- q. **(FCEV) EU mix 2030 HV:**EU primary resource mix → EU electricity mix 2030 → High Voltage grid + central electrolyser (hydrogen production) → pipelines (50km) + compression

The conversion pathways chosen, and the primary resources used have a strong impact on the results. The energy requirements and GHG emissions involved in each step are accounted (see annexes of JEC WTT report v5) and total WTT results are presented below by vehicle type (Table 1). The WTT figures reflect the net energy requirements and associated emissions to produce 1MJ of the final fuel. Energy expended is computed based on the Lower Heating Value (LHV) of the fuel and expressed in “MJ/MJ final fuel”. GHG emitted are expressed in “gCO_{2eq}/MJ final fuel”.

Table 1: WTT energy expended (MJ/MJ) and WTT GHG emitted (g CO_{2eq}/MJ) for the studied pathways (Prussi, Yugo, De Prada, Padella, Edwards, et al., 2020a)

Fuel pathways	WTT Energy expended (MJ/MJ final fuel)	WTT GHG emitted (g CO _{2eq} /MJ final fuel)
(ICEV) Diesel	0,3	19
(BEV) Nuclear	2,9	4
(BEV) Wind	0,1	0
(BEV) LNG	1,2	130
(BEV) piped NG	1,1	127
(BEV) EU mix 2016	1,9	106
(BEV) EU mix 2030	1,3	72
(FCEV) Nuclear	5,2	6
(FCEV) Wind	0,9	10
(FCEV) LNG	2,5	208
(FCEV) piped NG	2,3	202
(FCEV) SMR	0,8	101
(FCEV) SMR + CCS	0,8	40
(FCEV) EU mix 2016 MV	3,7	175
(FCEV) EU mix 2030 MV	2,7	119
(FCEV) EU mix 2016 HV	3,7	175
(FCEV) EU mix 2030 HV	2,7	118

Tank-to-Wheels

The variable that determines the **TTW** assessment is the powertrain. For diesel, the **internal combustion engine** operating in compression ignition mode is considered. For the alternative energy carriers, electrified propulsion systems are considered with the **battery electric**

vehicle for electricity and **fuel cell electric** vehicle for hydrogen. The HDV configuration analysed in this case study is the “tractor semi-trailer combination, with 40 tons gross vehicle mass rating and 14.290 tons in weighted payload, designed for use in long-haul mission” defined as group 5 vehicle in the TTW JEC report v5. The set of data retrieved from the JEC report (fuel consumption, energy consumption, CO₂ and CO_{2eq} emissions), for group 5 vehicle in weighted payload conditions for 2016 and 2025 are presented in the tables (Table 2, Table 3 and Table 4).

Table 2: Results group 5 Long Haul 2016 for ICE, BEV, and FCEV configurations with weighted payload (Röck et al., 2020, pp. 58–59)

2016; Group 5 Long-haul with weighted payload (14290 kg)							
Fuel	Propulsion system	Fuel consumption		Energy consumption		CO ₂ g/tkm	CO _{2eq} g/tkm
		liquid l/100km	gas kg/100km	without charging losses MJ/tkm	with charging losses MJ/tkm		
BO (diesel)	ICE CI	29,04		0,7292		53,38	55,52
el grid	BEV			0,3731	0,424	0	0
H2	FCEV		6,943	0,5829		0	0

Table 3: Results group 5 Long Haul 2025 for ICE, BEV, and FCEV configurations with weighted payload (Röck et al., 2020, pp. 58–59)

2025; Group 5 Long-haul with weighted payload (14290 kg)							
Fuel	Propulsion system	Fuel consumption		Energy consumption		CO ₂ g/tkm	CO _{2eq} g/tkm
		liquid l/100km	gas kg/100km	without charging losses MJ/tkm	with charging losses MJ/tkm		
BO (diesel)	ICE CI	26,3		0,6603		48,34	50,31
el grid	BEV			0,2889	0,328	0	0
H2	FCEV		5,712	0,4795		0	0

Table 4: Summary of fuel properties used for the Well-To-Wheels integration (liquids) (Prussi, Yugo, De Prada, Padella, & Edwards, 2020, p. 41)

Fuel properties							
Fuel type	Description	Density (kg/m ³)	CN	LHV (MJ/kg)	elemental composition of carbon (%m)	CO ₂ emission factor (g/MJ)	CO ₂ emission factor (kg/kg)
Diesel BO	Diesel fulfilling EN590, with no FAME addition.	832	51	43,1	86,1	73,2	3,16
Hydrogen (CGH ₂)	Compressed hydrogen at 700 bar.	0,084	-	120	0	0	0

The TTW energy consumption, is based on LHV of the consumed fuel and on the amount of electricity used. It was computed in “kWh/km” with the following calculation:

$$TTW_{energy} \left(\frac{kWh}{km} \right) = \frac{\left(TTW_{energy} \left(\frac{MJ}{tkm} \right) * payload (t) \right)}{3.6}$$

The TTW GHG emissions, expressed in “g CO_{2eq}/km” are based on the carbon content of the consumed fuel.

$$TTW_{GHG} \left(\frac{g \text{ CO}_2eq}{km} \right) = TTW_{GHG} \left(\frac{g \text{ CO}_2eq}{tkm} \right) * payload (t)$$

Results from the TTW energy expended and GHG emissions are listed in the table below (Table 5).

Table 5: TTW energy expended (kWh/km) and TTW GHG emitted (g CO_{2eq}/km) for the studied pathways

Powertrain	TTW Energy expended (kWh/km)		TTW GHG emitted (g CO _{2eq} /km)	
	2016	2025	2016	2025
ICEV	2,9	2,6	793	719
BEV	1,7	1,3	0	0
FCEV	2,3	1,9	0	0

2.2.2. WTW integration and calculations

The WTW results are the combination of the WTT and TTW results and reflect the environmental performance in two ways:

- WTW_{energy} for the total energy expenditure expressed in “kWh/km”; it represents the total primary energy expended to move the vehicle over one km
- WTW_{GHG} for the total GHG emitted, expressed in “g CO_{2eq}/km”; it represents the total GHG emitted to move the vehicle over one km

Following calculations were used:

$$WTW_{energy} \left(\frac{MJ}{km} \right) = TTW_{energy} \left(\frac{MJ}{km} \right) * \left(1 + WTT_{energy} \left(\frac{MJ}{MJ} \right) \right)$$

$$WTW_{energy} \left(\frac{kWh}{km} \right) = WTW_{energy} \left(\frac{MJ}{km} \right) / 3.6$$

$$WTW_{GHG} \left(\frac{g CO_2eq}{km} \right) = TTW_{GHG} \left(\frac{g CO_2eq}{km} \right) + WTT_{GHG} \left(\frac{g CO_2eq}{km} \right)^{**}$$

$$^{**}WTT_{GHG} \left(\frac{g CO_2eq}{km} \right) = TTW_{energy} \left(\frac{MJ}{km} \right) * WTT_{GHG} \left(\frac{g CO_2eq}{MJ} \right)$$

To assess the environmental performance, both the energy efficiency and GHG emissions are relevant indicators as they reveal which solution implies fewer primary sources exploitation and which solution provides the biggest contribution to GHG emission reductions. Although, a solution offers an advantage in terms of GHG emissions, it might have a worse energy efficiency or the other way around. It is important to emphasise that overall conclusions on the most efficient routes, in terms of energy and GHG emissions, can only be drawn if the whole WTW analysis is considered, as both the upstream efficiencies and the powertrain efficiencies have a strong impact on the results.

3. Literature review

3.1. The role of heavy-duty vehicles in the energy transition

3.1.1. The transportation sector

The transportation sector is one of the biggest source of greenhouse gas (GHG) emissions globally (IEA & OECD, 2017), in 2019 it accounted for 27% of European GHG emissions (EEA, 2020) and 21% in Belgium (European Union, 2021). Therefore, decarbonising the transportation sector will play a crucial role in the reduction of emissions, in particular the road transport which is the largest contributor to transport emissions (EEA, 2020). The transport demand will keep increasing along with emissions; due to rising income, population growth, international trade and expansion of e-commerce, which is urging the call for action (IEA, 2020a).

The transportation sector is also consuming a lot of energy and represents more than 50% of total oil demand. Moreover, it emits air pollutants through fuel combustion, harming the environment and human health. Regulations to minimize air pollution and standards to improve fuel economy are already implemented in the car market and are slowly applied in the heavy-duty market. Regions and cities are even starting to outlaw internal combustion or diesel engines, promoting the zero- and low-emission vehicles which produce, respectively, no and a limited amount of tailpipe emissions (e.g. BEV or FCEV). (IEA, 2020a)

Cutting down CO₂ emissions and oil use in the transport sector is a great challenge. It will involve new uses and modes of mobility with a switch to decarbonised fuels and improved energy efficiency (energy output/energy input). Innovation and a large assortment of technologies are required to support the transition. For long-distance transport modes; heavy-duty trucking, maritime shipping, and aviation; the challenge to switch to alternative fuels and technologies is even greater because of their energy and power density requirements. Besides technology readiness, resource availability and costs need to be considered taking into account the cost of new infrastructure. (IEA & OECD, 2017)

Belgium has set a target of 27% reduction in transport emissions by 2030 compared to 2005's levels. It wants to achieve this by rising fiscal incentives for low emission vehicles, increasing the share of electromobility and foster active modes of transport. Belgium wants to develop electric vehicles along with a surge of 23.7% of renewable energy in the transport sector by 2030. (European Union, 2021)

3.1.2. Heavy-duty vehicles: Environmental, social, and economic impact

As mentioned earlier, road transport is the largest contributor to transport emissions. In 2019, the heavy-duty vehicles (HDV) in Europe were responsible for about a quarter of road transport CO₂ emissions and represented 6% of total European CO₂ emissions (European Commission, 2019). Heavy-duty trucks⁶ are representing the majority of these emissions, which are expected to continue rising due to larger economic activity and a surge of demand for goods, involving growing numbers of deliveries and road freight transport (IEA, 2020a). The EU, to align with The Green Deal targets and reach carbon neutrality by 2050, has set CO₂ standards to cut down average emissions from HDV, coming into effect as from 2025. The regulation requires new manufactured heavy-duty trucks to reduce the average emissions by 15% for 2025 and 30% for 2030, compared to 2020. The regulation also provides a system to encourage the adoption of zero- or low-emission vehicles, while ensuring technological neutrality. (European Commission, 2019)

Road transport also represents the largest share of oil demand as it still mainly relies on petroleum as a fuel (IEA, 2020a; Malins et al., 2014; Offer et al., 2010). Currently, nearly all trucks drive on oil-based fuels and, therefore, are very sensitive to potential price shocks on the oil market and supply disruptions. In 2019, trucks were accountable for more than 12 million barrels per day (mb/d) or, in other words, 12.5% of the global oil demand. Heavy-duty trucks only constitute 6% of all road vehicles, but because of the long distances they travel, they use about one-third of total fuel and up to 60% of the diesel consumption in road transportation. Trucks are also more energy intensive than trains and maritime ships, respectively they use only 30% and 10% as much energy per unit of cargo as trucks. (IEA, 2020a)

The challenge is that road freight transport is an important component of economic activity and is essential in the supply chain of companies. Since economic growth and road freight transport activity growth are interlinked, as long as there is economic growth the number of HDV on the road will continue to increase and so will the energy expenditure and emissions. (IEA & OECD, 2017) There are few options to dissociate road freight activity from economic activity, as there are not many convenient alternatives to trucks for inland freight transport.

⁶ A mix of rigid body and articulated trucks with a gross vehicle weight of greater than 15 tonnes (IEA & OECD, 2017).

Inland water channels and railways could take a larger share of the freight market, but the infrastructure is not always existent and it is not always possible to construct it. (IEA, 2020a)

Besides GHG emissions, which are contributing to global warming, road freight is also a major source of pollutants emissions degrading the air quality and harming human health (IEA, 2020a). Countries that continue to rely on fossil fuels, from which the combustion is the main cause of climate change and air pollution, will more certainly have a considerable economic disadvantage. It has been estimated that for the fifteen biggest emitters, the health impacts of pollutants will cost more than 4% of countries' GDP (WHO, 2021). Moreover, standards to limit pollutant emissions are expanding globally, forcing for instance, trucks with internal combustion engines to use pricy aftertreatment systems to curb air pollutions. Standards will be stricter with time and aftertreatments costs will surge, offering an advantage to zero- and low-emissions vehicles. (IEA, 2020a)

To enable a smooth transition towards decarbonised HDV, the EU needs to provide an inclusive and supportive framework to foster innovation and sustain EU's technological lead in the mobility. This implies that public and private actors invest in R&D, a bigger provision of zero- and low-emission HDV, deployment of charging and refuelling stations, an integrated energy system, and foremost, for batteries a sustainable supply, production, reuse and recycling program needs to be set up in Europe. (European Commission, 2019)

So, reasons to switch from the conventional oil based HDV to alternatives are multiple. The high dependency on oil makes organizations vulnerable to price shocks and the future increase in oil prices. The combustion of fuels, posing a significant threat to the environment and to human health, sees a growing number of regulations on GHG emissions and air pollutants. However, to ensure a successful transition it requires an integrated and consistent approach amongst European countries with incentives to encourage the adoption of zero- and low emission HDV. The role of companies to be an active actor of change is discussed in the following section.

3.1.3. Supply chains: companies' responsibilities

Climate consensus is urging governments and organizations to take action now. Governments are slowly developing new regulations and introducing additional incentives to orientate companies and economic growth towards a low-carbon direction. (GHG Protocol, 2011) Until

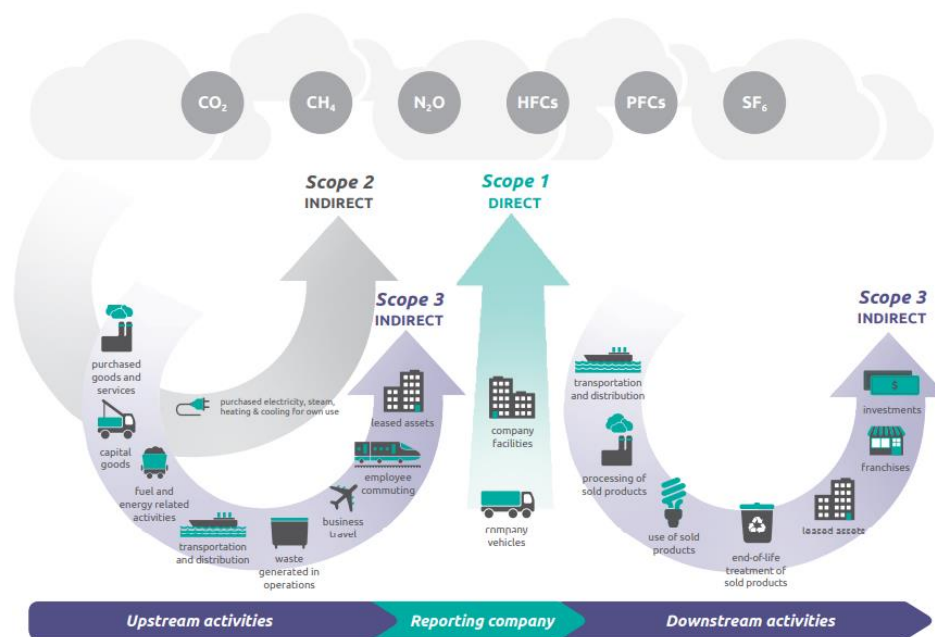
now, to curb air pollution passenger vehicles have been more regulated than HDV, although they account for the major share of oil demand and CO₂ emissions. With the CO₂ emission standard coming into force for heavy-duty trucks in 2025, it will become mandatory (for manufacturers) to report on fuel consumption and emissions. (IEA, 2020a)

But political actions are not sufficient, organizations need to take the lead and embrace the sustainability path. To prepare for the transition, companies need to adapt their strategy now, to become resilient for future disruptions. The European commission is already requiring some large companies to disclose on the non-financial performance through the Corporate Sustainability Reporting Directive, setting a step closer to mandatory reporting. There is a growing interest from investors, NGO's, consumers, policy makers and other stakeholders to assess the sustainability performance of companies, pushing them to integrate environmental and social aspects into business. (European Commission, 2021) Companies are already starting to report their sustainability performance on voluntary basis to increase transparency. The exercise of reporting is also pushing companies to measure their emissions and, thus, identifying where to focus reduction activities. The Greenhouse Gas Protocol aims to provide a standardised framework to build up a GHG emissions inventory. It categorizes the direct and indirect GHG emissions of organizations into three "scopes":

- Scope 1 covers direct emissions from owned or controlled sources.
- Scope 2 covers indirect emissions from the generation of purchased electricity.
- Scope 3 covers indirect emissions that range from the goods the organization purchases to the disposal of the products it sells. These are emissions coming from sources that organizations do not control and typically come from supply chains. (GHG Protocol, 2011)

HDV emissions, depending on whether they are owned or not by the company, will be either classified in scope 1 accounting for direct emissions produced by the combustion of fuels from owned vehicles, or in scope 3 accounting for indirect emissions from the upstream or downstream third-party transportation of purchased or sold goods. The road freight transport has a critical role to play in the reduction of emissions both within companies own operations and throughout their value chains. (GHG Protocol, 2011)

Figure 2: Overview of GHG Protocol scopes and emissions across the value chain (GHG Protocol, 2011, p. 5)



Covid-19 has caused severe disruptions in road freight operations with lockdowns, facilities closing, supply and demand shocks, pushing companies to redesign supply chains. This has direct near-term consequences for fleet effectiveness; it will speed up the withdrawal of the oldest and least efficient trucks and give large fleets the chance to leverage operational and technical efficiency gains. Despite many corporations struggling in this economic context, companies like Amazon, with a robust digital focus and data analytics capacities, have seen their share prices soar. (IEA, 2020a)

Nevertheless, decarbonising heavy-duty trucking reveals to be more difficult than other sectors (ETC, 2018). In the short-term, improving the fuel economy could cut down fuel consumption but companies are usually using trucks for more than 10 years which is slowing down the process of replacement. Additionally, afterwards trucks are often being sold from developed to developing countries where they have a second life. (IEA, 2020a) According to the International Energy Agency (2020a), the primary obstacles to switch to zero-emission trucks are the limited model range, higher acquisition prices and poor infrastructure. However, emission reduction levers exist and are listed in the next section.

3.1.4. Impactful emission reduction levers for heavy-duty vehicles

Four broad solutions to decarbonise road freight have been selected from the literature: systemic improvements in operations and logistics, vehicle efficiency, shift of transport mode, low-carbon alternative fuels.

a. Systemic improvements in operations and logistics

Road freight transport operations often rely on complex logistical system that organizes the movement of goods from one point to another and aims to meet customer expectations while using the least amount of resources. Optimizing operations and logistics is a measure easy to implement in the short-term with low barriers and it enables the reduction of road freight trucking activity and reach more efficiency on the road. This includes for instance, optimization of routes, scheduling deliveries when traffic is low, fuel efficient driving training for truck drivers, measures to ensure deliveries with trucks fully loaded and avoid empty returns (i.e. collaborating with other companies). (Amant et al., 2020; ETC, 2018; IEA & OECD, 2017; Moultak et al., 2017) Further, in the medium-term, adopting automation (i.e. platooning, autonomous trucks) and information and communication technologies (i.e. digital freight matching to fill to optimal load) could transform the sector completely (IEA, 2020a; IEA & OECD, 2017). Such measures could reduce up to one third of CO₂ emissions (Moultak et al., 2017).

b. Vehicle/energy efficiency

Vehicle efficiency can be enhanced for both existing and new trucks and will reduce energy expended and GHG emitted. Improving powertrain efficiency, using low rolling resistance tires, using lightweight materials, aftertreatment technology and aerodynamics are vehicle efficiency measures that can be applied to new trucks or retrofitted in the existing fleet and are cost-effective (with payback periods estimated between 2 to 4 years). These technologies are interesting to reduce emissions in the short-term but have limited impact on the long-term as deep decarbonisation is needed to reach climate targets. (Calvo Ambel et al., 2017; IEA & OECD, 2017; Moultak et al., 2017; Smallbone et al., 2020) The estimations of fuel consumption reduction enabled by vehicle efficiency gains with cost-effective and advanced technologies vary in the literature due to large variability of assumptions. In the Sustainability Development Scenario of IEA (2020a) energy efficiency technologies for heavy-duty trucks

could curb fuel consumption down by 15% to 25% in 2025 and by 25 to 35% in 2035 compared to a 2015 baseline. Delgado, Miller, Sharpe & Muncrief (2016) find an even greater potential for efficiency technologies in their study for EU's tractor-trailers, reaching a fuel consumption reduction up to 40% between 2030 and 2045 depending on the improvement rate per year.

c. Shift of transport mode

Encouraging a modal shift towards more carbon-efficient mass transport will also help reduce emissions (Amant et al., 2020; ETC, 2018; IEA, 2020b). As mentioned earlier, heavy-duty trucks are more energy intensive than other transport modes. They require about 70% more energy than trains and about 90% more than ships (IEA, 2020a). Since 75% of inland freight is operated by road, a consequent part could be switched to inland waterways (especially in Nordic countries) or rails, depending on specific regions and available infrastructure (Amant et al., 2020; ETC, 2018; IEA, 2020b). Since trucks offer many advantages for freight transport such as their flexibility, speed and cost it will remain the favourite option. The EU is trying to support more rail freight under the TEN-T framework, by improving freight corridors and growing the market share of rail by 5%. (Calvo Ambel et al., 2017; Earl et al., 2018) This would not only contribute to reduce emissions but also to reduce road traffic and accidents.

d. Low-carbon alternative fuels

Above mentioned emission reduction levers, even in a scenario where they are adopted widely, would not be sufficient to deliver a net reduction in GHG emissions and fuel consumption in 2050 compared to 2015. To completely decarbonise the road freight sector, it will require more far-reaching strategies, including the substitution of diesel for alternative fuels. (IEA, 2020b; Lee et al., 2018; Moulak et al., 2017; Sacchi et al., 2021) Alternative fuels complement the energy efficiencies improvements by dealing with the environmental, social, and economic issues caused by dependency on oil. Indeed, by diversifying energy sources it leverages the economic advantages, decreases air pollutants emissions harming human health and the environment and provide a long-term solution for a deep decarbonisation of the road freight sector. In line, energy policies aimed at reducing emissions from transport and diversify the mix of energy sources encourage the use of alternative fuels and energy carriers. Consequently, there are already a lot of alternative fuels that are being studied, tested and some are already commercialized. Biofuels, natural gas, electricity, and hydrogen

are the most relevant fuels with the potential to contribute to a low-carbon transition, if strict regulation and advanced technology support it. But to have a real impact on GHG emissions reductions it will require that fuels are also decarbonised upstream including their production and distribution pathways. Moreover, other challenges arise such as heavy costs, indirect land use changes for biofuel production, methane slip for natural gas and the use of scarce resources for the manufacturing of batteries. (IEA & OECD, 2017)

To summarize, operational and technical improvements contribute to cut down the carbon intensity and deliver short- and medium-term energy efficiency savings, while the shift to low carbon fuels and electric powertrains delivers long term emissions reductions and will be necessary to reach climate targets. In the Sustainability Development Scenario, IEA (2020b) claims that for heavy-duty trucks, “operational and technical efficiency together contribute nearly 45%, electricity an additional 31%, and hydrogen and biofuels together almost 35% of cumulative CO₂ emission reductions”. In the section 3.1.5., the solution of alternative fuels will be furthered explored.

3.1.5. Potential alternative fuels and powertrains

In order to assess the environmental performance of alternative fuels it requires the analysis not only of the fuel use but also the fuel production, transformation, distribution and final use; defined as the Well-To-Wheels (WTW) pathway. (IEA & OECD, 2017) The final use of the fuel occurs in its corresponding powertrain, for instance diesel is stored in a tank and combusted in an internal combustion engine (ICE). But some alternative fuels need new powertrain configurations, such as electricity and hydrogen which require an electric motor and a battery.

Biofuels, natural gas, electricity, and hydrogen are available alternative fuels that can be combined with existing and/or future powertrains. All these alternatives need to be considered as a combination of solutions will accelerate the transition. IEA (2020b) and ETC (2018) forecast that for heavy-duty trucks, biofuels and natural gas will play a transitional role and will then be surpassed by electricity and hydrogen as these will become cost-competitive and more available. This prediction is verified in the literature, but the time frame varies between 2030 and 2050 (Calvo Ambel et al., 2017; Lombardi et al., 2020; Moultak et al., 2017; Sacchi et al., 2021; Smallbone et al., 2020; van der Zwaan et al., 2013).

The use of **biofuels** for trucks is expected to grow in the near-term due to their high energy density and, for some biofuel options, their compatibility with existing vehicle fleet as no change is required in terms of fuel distribution and vehicle technology (liquid biofuels can even be blended with conventional fuels). However, conventional biofuel (produced from food crops) poses some sustainability issues such as the competition for cultivable land for food and direct and indirect land-use change impacts, which can cause biodiversity loss (Amant et al., 2020; IEA & OECD, 2017; Malins et al., 2014). Advanced biofuels (produced from residues and wastes from the agriculture, forestry, and food industries, or from non-food crops grown on marginal land) in counterpart could diminish these sustainability risk. Nevertheless, the production pathway requires complex processing, thus substantial energy inputs. To remain carbon neutral, renewable energies need to be used upstream, which is not always the case until now. So feedstock choice will be crucial to provide real decarbonisation solutions. (IEA & OECD, 2017) Biofuels will contribute to diversify the transport fuel supply and reduce CO₂ emissions to a certain extent, but do not provide sufficient potential reduction for a deep decarbonisation (Calvo Ambel et al., 2017; European Commission, 2019; IEA, 2020b).

Concerning **natural gas**, some regions with favourable policies, have seen a shift to liquified natural gas (LNG) for long-haul trucking and a shift to compressed natural gas (CNG) for trucks with shorter distances and lower usage. The shift to natural gas reduces CO₂ emissions and air pollutant emissions improving the air quality. However, the natural gas consumption remains moderate, demonstrating the insufficient potential to cut down GHG emissions on a WTW basis with regards to methane issues⁷. There is a risk of leakage in production, processing, transmission and distribution and methane is considered as having a high global warming potential (GWP). Besides the methane slip risks, heavy-duty engines using natural gas have often a lower efficiency than diesel, which is sometimes counterbalancing the decreased carbon intensity of natural gas.(IEA, 2020a; IEA & OECD, 2017)

⁷ "Vehicles using methane as a fuel face the issue of the incomplete combustion of the methane, termed "methane slip". Given the high global warming potential of methane, this issue limits significantly the CO₂ emission benefits that are attributable to the lower carbon content of methane in comparison with diesel, especially for natural gas (biomethane delivers much higher well-to-wheel GHG emissions reductions and is, therefore, less affected by this drawback)".(IEA & OECD, 2017)

The conventional internal combustion engine fuelled by diesel presents economic and technological advantages for heavy-duty trucks due to cheap primary energy and large-scale production. Moreover, the high energy density (volumetric (energy/volume) and gravimetric (energy/mass)) of diesel is appealing for long-distance vehicles, with high energy working cycles and short refuelling time. (Smallbone et al., 2020) Keeping only conventional diesel trucks in the fleet will not be an option to respect EU's CO₂ standards and meet climate targets. In the long-term, zero-emissions vehicles such as battery electric vehicles (BEV) and fuel cell electric vehicles (FCEV), are essential to decarbonise trucks. So **electricity** and **hydrogen** will dominate the fuel mix of trucks, consequently the use of electric powertrains will exceed the use of internal combustion engines. (Calvo Ambel et al., 2017; IEA & OECD, 2017; Lee et al., 2018; Moultak et al., 2017; Sacchi et al., 2021) Batteries and fuel cells are therefore a key technology for a decarbonised future. Until now, since long-haul trucks are travelling long distances and use a lot of energy due to heavy payloads, electric batteries have not been used widely due to their long recharging time and low volumetric and gravimetric energy density resulting in heavy battery load and lower autonomy. On the contrary, hydrogen has a higher gravimetric energy density reducing the mass and making FCEV more suitable for long-haul as they have better autonomy but also shorter refuelling time. However, the volumetric energy density is still lower than conventional fuel, consequently, hydrogen storage takes up four times more space than diesel tanks for the same range. (IEA & OECD, 2017; Offer et al., 2010; Smallbone et al., 2020)

Nevertheless, battery electric and hydrogen fuel cell electric trucks present major advantages. Firstly, they emit no tailpipe emissions meaning the air quality improves considerably and they help reducing CO₂ emissions. Secondly, the energy efficiency⁸ of (fuel cell) batteries is up to 55% better than diesel engine. (IEA & OECD, 2017; Lee et al., 2018; Moultak et al., 2017; Offer et al., 2010; Smallbone et al., 2020) Lastly, both electricity and hydrogen can be produced from a large variety of primary energy sources such as renewable energies, nuclear

⁸ "When driving on an uncongested highway, a modern truck can achieve efficiencies from the engine to the wheel of no higher than 30%, while electric trucks can reach powertrain-to-wheel efficiencies of as high as 85% or more" (IEA & OECD, 2017). Although FCEV have an additional conversion loss when converting hydrogen in the fuel cell to electricity (about 35% energy loss), they offer about 50% efficiency and thus remain more efficient than diesel engine (IEA & OECD, 2017).

energy, natural gas, biomass, and decarbonised fossil fuels. This provides a chance to break the chain between transport and oil. (IEA & OECD, 2017; Offer et al., 2010)

The number of electric trucks entering the market is slowly increasing and requires technology advancement to develop fuel cells and batteries, considerable investment in infrastructure such as hydrogen refuelling stations, fast chargers and electric road systems that can charge trucks while they drive. (IEA & OECD, 2017)

However, the zero-emission vehicles using electric powertrains only means they do not emit GHG emissions during vehicle operations. Their ability to deeply decarbonise the heavy-duty road freight transport will depend on the carbon intensity in the production, transformation, and distribution pathways of the fuel. So, in order to assess the environmental performance it is necessary to conduct a WTW analysis taking into account the upstream and tailpipe emissions of the fuel. (IEA, 2020b; IEA & OECD, 2017; Lombardi et al., 2020; Moro & Lonza, 2018; Prussi, Yugo, De Prada, Padella, & Edwards, 2020; Rousseau & Sharer, 2004; Smallbone et al., 2020)

As a result, the next chapter will deep dive into the WTW assessment of three fuels, namely diesel, electricity, and hydrogen. The aim is to assess the environmental performance of electricity and hydrogen (alternative energy carriers), considering different potential production pathways and to compare them to diesel (conventional fuel). The focus is thus on electric drivetrains as they provide zero tailpipe emissions and a higher potential than biofuels and natural gas for deep decarbonisation of the transport sector in the long term.

3.2. Well-to-Wheels analysis of fuels and energy carriers for heavy-duty vehicles

This chapter provides the theoretical background to understand the production pathways of diesel, electricity, and hydrogen from “well” to “wheels”.

First, in section 3.2.1., the meaning of a Well-to-Wheels analysis is clarified, as well as its relevance to assess the environmental performance of trucks. The chapter is then broken down into three sections according to each final fuel, diesel, electricity, and hydrogen, to review their respective Well-to-Wheels pathways. The section 3.2.2. “Diesel”, first provides a background explanation of the fuel. Then the typical production chain of the fuel is explained. Finally, the use of diesel in the trucks is addressed by examining the efficiency of the powertrain, consisting of the diesel tank and the internal combustion engine. The section

3.2.3. “Electricity”, starts by describing the energy and its potential use for trucks. As electricity can be produced from multiple sources, the different pathways are investigated. Firstly, the EU electricity mix and Belgian electricity mix are addressed. The electricity mix of a country is the specific combination of different energy sources used to generate electricity for the grid. As such, each energy source is inspected, first within the EU and Belgian electricity mix to understand the context, then separately to review their supply chain. The latter, allows to identify the different energy efficiencies and GHG emissions upstream. Finally, the use of electricity in trucks is tackled by inspecting the efficiency of the powertrain, which includes the electric battery and motor. The section 3.2.4. “Hydrogen”, first gives an introductory explanation about the energy carrier. Hydrogen can either be produced from electrolysis (requiring electricity) or from natural gas. Therefore, these two production processes are dismantled to identify respective energy efficiencies and GHG emissions. Lastly, the use of hydrogen in trucks is explained by analysing the efficiency of its powertrain, mainly constituted by a hydrogen tank, a fuel cell, and an electric motor.

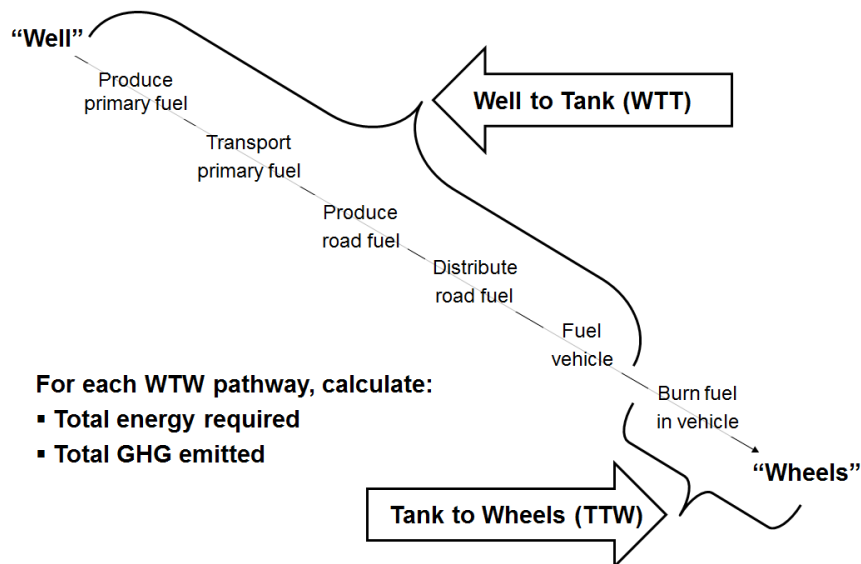
The previous sections allow to identify where energy consumption and greenhouse gas emissions occur in the process. For electricity and hydrogen multiple production pathways are investigated and thus their Well-to-Wheels results vary. The chapter is concluded with the comparison of the overall Well-to-Wheels results found in the studies from the literature. The section is divided in two parts, it analyses the energy efficiency and then the GHG emissions. Some first conclusions can be drawn and, later, will be compared with the results from the case study.

3.2.1. Well-to-Wheels analysis

The European Commission (2016) uses the **Well-to-Wheels (WTW)** analysis to assess the environmental performance of different combinations of fuels and powertrains by estimating their energy efficiency and GHG emissions. The WTW analysis can be divided in two parts, the **Well-to-Tank (WTT)** and **Tank-to-Wheels (TTW)** (Figure 3). The WTT considers energy expenditures and GHG emissions coming from the extraction of the primary energy source until final distribution to end user. Thus, this includes the production, transport, manufacturing, and distribution of road fuels. While the TTW accounts for energy expended and GHG emissions from fuel consumption in the vehicle, or in other words, the tailpipe emissions. A WTW analysis does not encompass energy and emissions from building

manufacturing facilities and vehicles or end of life processes, among others that would be accounted for in a full Life Cycle Analysis (LCA). (Prussi, Yugo, De Prada, Padella, & Edwards, 2020)

Figure 3: Well-to-Wheels analysis (European Commission, 2016)



The WTW analysis is broadly used in the literature to obtain a complete picture of the environmental impact when comparing fuels (Gustafsson et al., 2021; Lombardi et al., 2020; Mansour & Haddad, 2017; Prussi, Yugo, De Prada, Padella, & Edwards, 2020; Ramachandran & Stimming, 2015; Smallbone et al., 2020; Torchio & Santarelli, 2010). When assessing the environmental impact of different types of trucks, a WTW analysis of their fuel is sufficient, as the carbon weight of the equipment such as the (fuel cell) battery and tank are amortized, considering the high utilization and annual mileage of trucks (about 100.000km/year). This also shows the great potential of BEV and FCEV to decarbonise road freight transport as their effect becomes even more beneficial when used extensively. (Amant et al., 2020; Lombardi et al., 2020). So in the case of trucks, researches comparing their environmental performance are focused on their fuel life cycle emissions, rather than the whole vehicle LCA, as GHG emissions deriving from WTW processes are representative enough of the overall GHG emissions. (Gustafsson et al., 2021; Lombardi et al., 2020; Sen et al., 2017; Torchio & Santarelli, 2010). Although a complete LCA would give an even more comprehensive overview, since the production and end-of-life treatment of trucks and the equipment have a considerable impact, this impact does not vary much between different vehicles. Besides, literature about the LCA's of trucks is scarce and lacks of consistency in terms of scope and

methodology used. (Lee et al., 2018; Prussi, Yugo, De Prada, Padella, & Edwards, 2020; Sacchi et al., 2021)

In the literature many researches have partially based their calculations on the “JEC WTT report version 4.a” (Edwards et al., 2014). The JEC is a collaboration between the JCR (European commission’s Joint Research Centre), EUCAR (the European Council for Automotive Research and development) and Concawe (the European oil companies’ association for environment, health and safety in refining & distribution)(European Commission, 2016). They recently published an updated version “JEC Well-To-Wheels report version 5” which for the first time includes HDV in its scope (Prussi, Yugo, De Prada, Padella, & Edwards, 2020). The case study will be based on the data retrieved from the “JEC Well-To-Wheels report v5” and datasets since it is the most comprehensive, transparent, and recent compilation of WTT and TTW data for HDV in Europe. It evaluates a very wide range of alternative fuels and powertrains options, establishing the energy efficiency and GHG emissions for different relevant pathways for Europe in 2020 and beyond (European Commission, 2016).

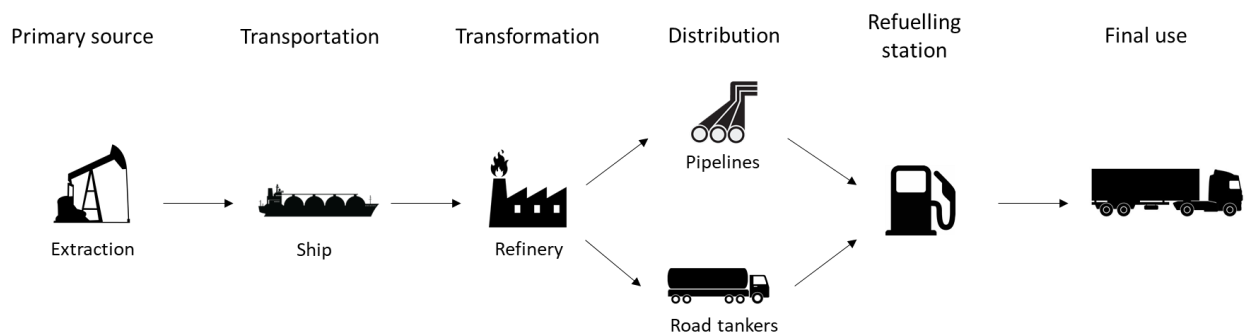
In the next sections of this chapter, diesel is compared to electricity and hydrogen on a WTW basis. For each final fuel the WTT and then the TTW parts are discussed. Therefore, different pathways to convert available primary energy sources into the final fuels are considered to evaluate their respective energy efficiencies and GHG emissions.

3.2.2. Diesel

Diesel engines are extensively used around the world for transportation, electric power generation, farming, mining, and construction. Diesel engines are preferred because they offer good fuel economy, a great source of power under almost any conditions and they last long. But because there has been a growing knowledge about the negative effects of diesel combustion, the composition of the fuel is being improved to decrease pollutants emissions. Moreover, advances in technologies for heavy-duty engines have also enabled the reduction in NO_x (nitrogen oxides) and PM (particulate matter) emissions, and future research will help to reduce those even more to achieve future emission standards. (Chevron Corporation, 2007) Also, exhaust aftertreatment systems are used to reduce the amount of NO_x which is done by adding Aqueous ammonia. Also known by the brand name AdBlue, this mixture of urea and water is commonly added to diesel.

The conventional internal combustion engine fuelled by diesel presents economic and technological advantages for heavy-duty trucks due to cheap primary energy and large-scale production. Moreover, the high energy density of diesel is appealing for long-distance vehicles, with high energy working cycles and short refuelling time. (Smallbone et al., 2020) Diesel is only produced from crude oil and, therefore, only one pathway is considered according to the common European case (Figure 4).

Figure 4: Production pathway for diesel



3.2.2.1. WTT: From primary energy resource to fuel

The Diesel WTT pathway includes crude oil extraction, transportation to refineries by ship, refining process near the markets and, finally, the distribution to the retail stations which is either done by road transport or by pipeline.

Crude oil extraction and transportation to market

The primary energy source of diesel is crude oil. Crude oil originates from different countries around the world and is mainly shipped as raw material to refineries. (Prussi, Yugo, De Prada, Padella, Edwards, et al., 2020b)

Refining and distribution

The crude oil is then turned into the final fuel, diesel, in local refineries often located at the coast (Antwerpen for Belgium). The refining of crude oil involves complicated processes to obtain the appropriate quality and quantity.

The diesel produced in the refineries is distributed by road tankers straight to refuelling stations or by pipeline to a depot. (Prussi, Yugo, De Prada, Padella, Edwards, et al., 2020b)

3.2.2.2. TTW: Powertrain

A HDV powered by diesel fuel is equipped with an internal combustion engine (ICE) operating in Compression Ignition (CI) direct injection mode. An Internal Combustion Engine Vehicle (ICEV) has a powertrain consisting of engine, transmission and axle (Röck et al., 2020). It is a basic configuration as the engine directly converts the fuel energy in mechanical energy, used via a gearbox and a transmission system to rotate the wheels (Lombardi et al., 2020). According to the JEC TTW report v5 (2020), an ICE CI has a peak efficiency of 45.8% for a 40 tons tractor-semitrailer. IEA & OECD (2017) confirm this result with an estimated peak brake thermal efficiency of 44-46%.

According to the IEA & OECD (2017) a modern truck can achieve **powertrain-to-wheel efficiencies up to 30%**. Lombardi et al. (2020) uses an ICE average efficiency of 35.1% for HDV up to 44 tons.

The energy content, or heating value, is an important characteristic of fuel, as it has a direct impact on the fuel consumption of the vehicle and thus CO₂ emissions. The energy consumed to move the vehicle over a certain distance, is based on the Lower Heating Value of diesel fuel. According to JEC TTW report v5 (2020), the LHV is 43.1 MJ/kg and the **CO₂ emission** factors is 73.2g/MJ. Due to low ICE efficiency the combustion of diesel requires high energy quantities and, therefore, causes high tailpipe emissions. For the TTW results, the report used a 40-ton long-haul truck with ICE CI engine with an estimated diesel consumption of 29.04 l/100km and an AdBlue consumption of 0.012 l/kWh.

3.2.2.3. WTW: Environmental performance

According to ICCT (2014) the emissions from WTT depend on the kind of crude oil and manufacturing process but account for about 18% of the WTW GHG emissions of fuel oils. The JEC WTT report v5 (2020b) estimates a lower contribution ranging between 5% and 10%. But estimating numbers from upstream emissions remains difficult due to lack of available data at oil field and the variation in refining processes. The major contribution to GHG emissions comes from the combustion of diesel itself in the vehicle, due to low efficiency of the powertrain.

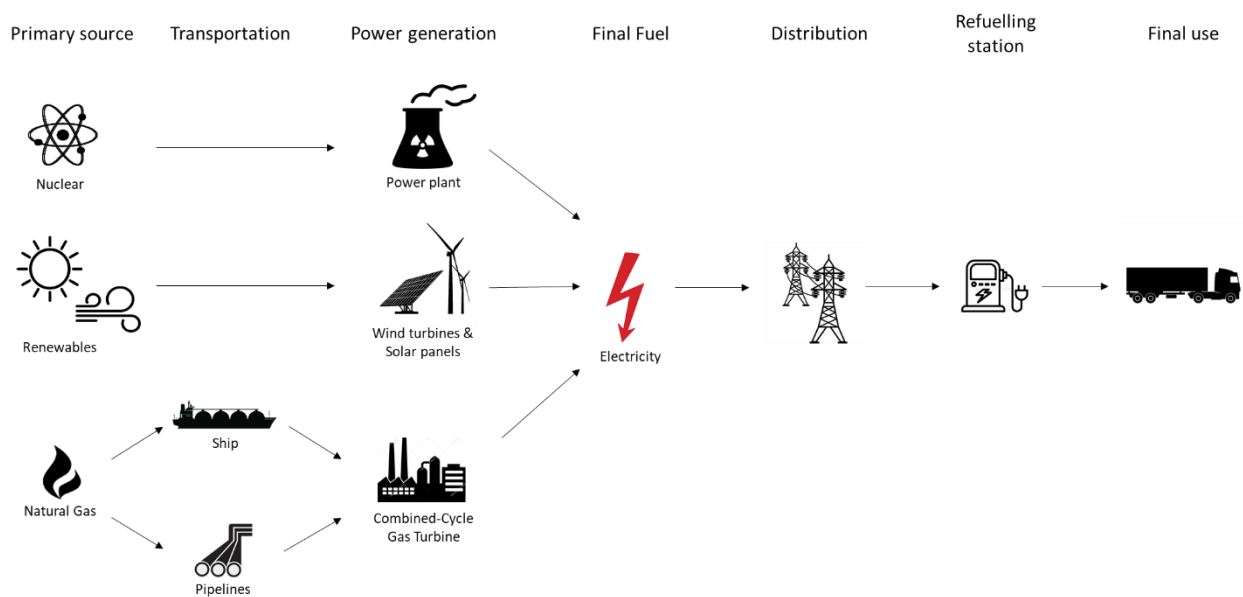
3.2.3. Electricity

Electricity is used in sectors such as building, industry and transport as well as to transform water to hydrogen by electrolysis. Electricity will play a key role for the transition to cleaner energy. The use of electricity as final energy has been increasing over years. Since 1990 the electricity demand increased by 3% annually. Demand in electricity will continue to grow since it is being applied in new sectors, driven by its environmental and practical benefits compared to other alternatives. It is expected to become the main form of energy for transport in the long-term. But a growing electrification requires electricity systems and supply to improve flexibility. As the surge in electric vehicles fleets imply more charging, it will increase electricity demand and could raise peak loads. In the meantime, with a growing share of renewable energy in the electricity mix from solar photovoltaic and wind power the issue of intermittency needs to be tackled. Thus electricity system need to become more flexible and the cost of storage technologies need to be reduced to deal with natural daily and seasonal variability of energy generation.(IEA, 2020a)

For heavy-duty trucks, BEV have an electric propulsion system with the electricity stored in batteries. Batteries are appealing for their high energy efficiency (electrochemical-to-mechanical) but limited by their low energy density, which reduces their autonomy. Electricity can be produced from many sources (fossil, nuclear, renewable) and its contribution as an energy carrier to decarbonise the road freight transport depends on its carbon intensity. The electricity mix used to charge the trucks will thus play a crucial role to reduce GHG emissions of the BEV.(IEA, 2020a; Moro & Lonza, 2018; Rangaraju et al., 2015)

Electricity is considered here as the fuel for the BEV and as energy carrier to produce hydrogen through water electrolysis. Since electricity can be produced from multiple energy sources, the EU-mix and BE-mix are discussed. The electricity mix is then broken down according to its primary energy sources (natural gas, nuclear, renewable) and the different production pathways are analysed (Figure 5).

Figure 5: Production pathways for electricity



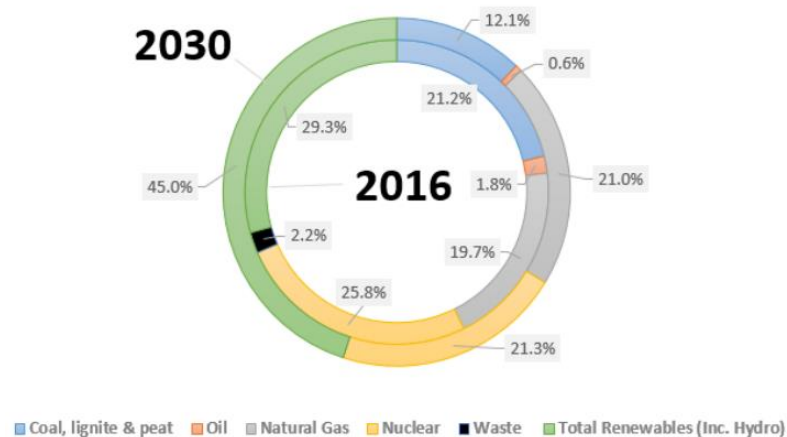
3.2.3.1. WTT: From primary energy resource to fuel

Electricity production

a) EU electricity mix

The EU electricity mix is a combination of different energy sources which is mainly composed of nuclear, renewables, natural gas, and coal. The EU electricity mix pathway represents a typical supply chain to produce electricity from the grid. So when electricity is taken from the grid, its carbon intensity will depend on the specific country's electricity mix. (Prussi, Yugo, De Prada, Padella, Edwards, et al., 2020b) The JEC WTT report v5 determines the EU electricity production mix for 2016 and projections for 2030 as presented in the chart below (Figure 6). The EU-mix in 2016 is based on data retrieved from Moro & Lonza (2018) and the European Environment Agency (2018). To predict the EU-mix in 2030 it is harder since it involves data about generating capacity and efficiency improvements in the future. Estimations have been based on historical data and the IEA NPC scenario (2020a).

Figure 6: EU electricity production mix (2016 data and projections for 2030) (Prussi, Yugo, De Prada, Padella, Edwards, et al., 2020b, p. 70)



Nuclear energy represented more than a quarter (25.8%) of total electricity produced in 2016 (EEA, 2018). Nuclear power plants provide energy for base load⁹ only because of technical aspects (long time to change power output, to start up, to shut down, ...) but also low fuel cost per power output. Despite their low operating costs and the fact that they are nearly carbon free, many European countries are planning to shut down nuclear power plants due to safety and radioactive waste issues. However, by 2030 the share of nuclear will still account for 21.3%. (Prussi, Yugo, De Prada, Padella, Edwards, et al., 2020b)

Renewable energy was dominating the EU-mix in 2016, satisfying 29.3% of the primary electric energy needs. Renewable energy in Europe is mainly produced from wind-, solar- and hydro-power. In 2016, wind electricity represented about 10% of total net electricity generation, solar 3% and hydropower up to 11% (Eurostat, 2018). By 2030, the share of renewables will increase as nuclear and coal will slowly be phased out. Wind is expected to contribute up to 26% of total electricity generation, solar 11% (European Commission, 2018) and hydro-power will remain between 11% and 13% as production capacity is reaching its limits. The production of electricity with renewable energy emits virtually no GHG emissions on a WTW basis (as it does not consider construction of wind turbines, solar panels, or hydroelectric power plants). (Prussi, Yugo, De Prada, Padella, Edwards, et al., 2020b)

Natural gas power plants represented 19.7% of the EU electricity generated in 2016 (EEA, 2018). Gas-fired power plants, as they start up fast, are useful to provide electricity during

⁹ "The amount of power made available by an energy producer (such as a power plant) to meet fundamental demands by consumers." (Merriam-Webster, n.d.)

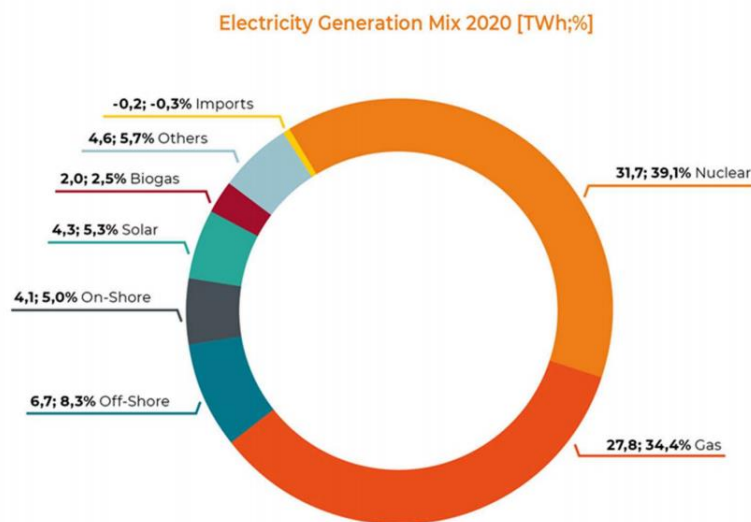
high demand. Thanks to their flexibility, they can compensate when renewable sources are insufficient. (Fluxys Belgium & Fluxys LNG, 2021) Gas-fired power plants normally use a gas turbine cycle (Brayton cycle). But by using the waste heat from the air in the Brayton, to produce steam, that can be used in a steam turbine cycle (Rankine cycle), it offers a much better efficiency, since electricity is produced twice from the same natural gas input: once by the turbine of the Brayton cycle, once by the turbine of the Rankine cycle. If the Brayton gas turbine cycle is coupled with the Rankine steam turbine cycle it refers to Combined-Cycle gas turbine (CCGT). (Langston, 2014) The CCGT is widely used in Europe as it generates 50% more electricity than the Brayton gas turbine cycle on its own. Thanks to the high efficiency of CCGT, which is up to 60%, and low carbon intensity of natural gas, the gas-fired power plants have a lower level of GHG emissions than coal or oil power plants. Natural gas has a reasonable low cost, has a better environmental performance than oil and coal and its supply is estimated to increase (by pipeline and by ship in form of liquefied natural gas (LNG)). Therefore, by 2030, its share in the EU-mix will slowly increase to 21% replacing the nuclear and coal energy. (Prussi, Yugo, De Prada, Padella, Edwards, et al., 2020b)

Coal fuels still accounted for 21.2% of the electricity production in 2016 (EEA, 2018). Coal is an affluent fossil fuel, with major resources located in stable political countries. As a low-cost primary energy source for power generation, coal-fired power plants are generally used to generate electricity for base load. However, as a carbon intensive fuel, coal results in greater GHG emissions than alternative technologies. (Prussi, Yugo, De Prada, Padella, Edwards, et al., 2020b)

b) BE electricity mix

Elia (2021) the electricity transmissions system operator in Belgium, has gathered the data about the Belgian electricity production mix in 2020 (Figure 7)

Figure 7: Belgian electricity generation mix in 2020 (Elia Group, 2021, p. 5)



Although there has been a little decline in **nuclear** generation, it remained the major electricity source in 2020 for Belgium. The electricity production mix was for 39.1% generated by nuclear power coming from the seven nuclear reactors, 4 located in Doel and 3 in Tihange. (Elia Group, 2021; European Union, 2021). Belgium has passed legislation to phase-out nuclear power plants between 2022 and 2025, posing a great challenge to the country to substitute such a significant share of the electricity generation in a short period of time (Elia Group, 2017; European Union, 2021).

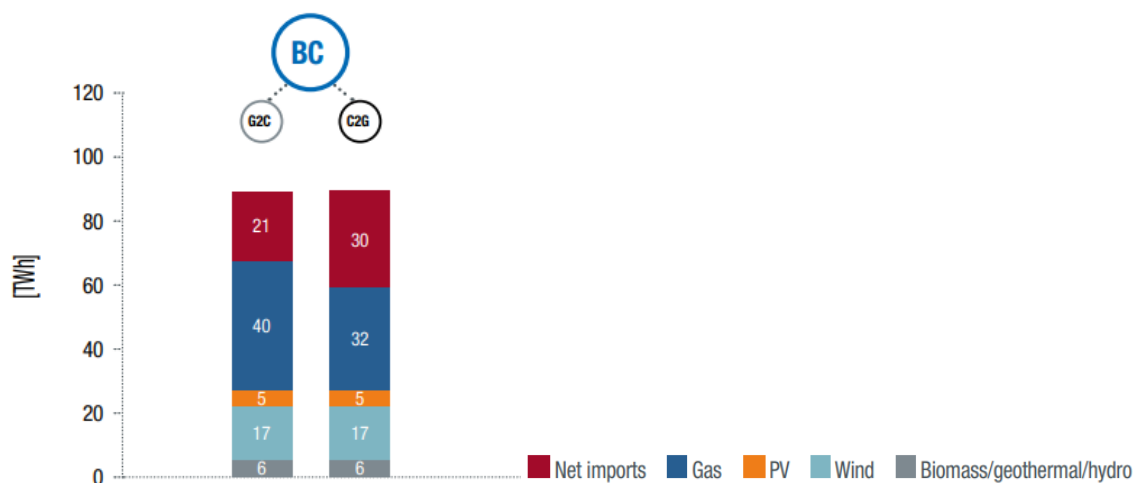
Next, **natural gas** represented 34.4% of the electricity production mix in 2020. The electricity generated by natural gas has been quite stable over the last years. The gas-fired power plant fleet has not evolved much recently, apart from Seraing (470 MW) and Vilvoorde (255 MW), which were put back into operation in October 2018. (Elia Group, 2021) In light of the phase-out of nuclear power plants combined with an intended shutdown of older gas-fired power plants, two third of current electricity generation in Belgium will vanish. It is therefore necessary to build replacement capacity, which is estimated by Elia (2017) to amount to a total of 3.6 GW. Therefore, the construction of new power stations, with a higher proportion of CCGT, are required to guarantee security of supply and also to remain competitive with our neighbours. (Elia Group, 2017)

In 2020, 18.6% of electricity was generated by **renewables** which is the highest level ever seen in Belgium and represents an increase of 31% compared to 2019. The surge in renewables is mainly a consequence of optimal weather conditions and increased installed capacity from

wind power (4670MW in total) and solar power (4788 MW in total). Wind generation was higher during the winter and the majority of solar energy was generated in summer, making both energies complementary. (Elia Group, 2021)

Elia has also made prediction about the future Belgian production mix based on three different scenarios. This paper will use the “base case” scenario with the gas-before-coal (G2C) strategy (Figure 8) as main assumption for the Belgium production mix evolution. This scenario represents “the minimum that has to be achieved to reach the EU 2030 targets” (Elia Group, 2017) where new natural gas power stations with a higher proportion of efficient units (CCGT) is considered the best option. By 2030, the electricity production mix is composed of renewable energy sources and gas-fired units, with gas as principal fuel for the transition in Belgium (Elia Group, 2017; European Union, 2021). While further cross-border exchange is growing with a fairly high (23.6% versus net zero in 2020) import rate in this case. The Belgian electricity mix in 2030 will have a 31.4% share of generation by renewables, 45% share of generation by natural gas and 23.6% of electricity will come from net imports. (Elia Group, 2017)

Figure 8: Electricity production mix and cross-border exchanges in Belgium with 100% CCGT (Elia Group, 2017, p. 88)



In light of the nuclear phase-out and an increase in fossil-fuel based electricity (natural gas) to compensate the lost in nuclear power, the carbon intensity of the electricity mix will increase. Moreover, with an increase of electric vehicles this will require even more power production capacity. (Ramachandran & Stimming, 2015) Also, the carbon intensity of electricity mix used to charge an electric vehicle or to produce hydrogen, will have a significant impact on the GHG emissions on a WTW basis (Moro & Lonza, 2018; Rangaraju et al., 2015).

The main primary sources of current and future electricity generation in Belgium are further discussed with regards to their environmental performance in the WTT pathway.

c) Nuclear

Nuclear energy is produced from uranium and more precisely the U_{235} isotope which is abundant on earth. Uranium is mainly imported from Russia (Statista, 2020). Nuclear electricity is virtually **carbon free** with the only considerable CO_2 emissions occurring upstream during mining, transport, and enrichment of the uranium and also for the maintenance of the nuclear reactors. A nuclear power plant is very similar to a conventional thermal power plant. The difference is that the heat, which is used to generate the steam that powers the steam turbines and the electrical generator, is not produced by burning gas, coal, or oil, but with the energy obtained from the fission of heavy elements such as uranium. However, nuclear power plants have **low thermal efficiency** (33%), meaning only a small part of the primary energy is caught, thus, creating big energy losses and also radioactive waste. (Towler, 2014, Chapter 7) It is not considered as a renewable energy because of radioactive waste disposal and safety issues. As a result, the development of nuclear fission as a key energy resource is a societal dilemma. Despite their low operating costs and the fact that they are almost carbon free, many European countries are planning to shut down their aged nuclear power plants. (Prussi, Yugo, De Prada, Padella, Edwards, et al., 2020b; Ramachandran & Stimming, 2015)

d) Renewable energy

Renewable energy is produced from sources which are virtually inexhaustible. Major renewable sources in Europe are wind-, solar- and hydropower. On a WTW basis, electricity generated by renewables emits no **GHG emissions**, except from some fossil energy consumed during maintenance of installations. (Prussi, Yugo, De Prada, Padella, Edwards, et al., 2020b)

Wind turbines present a high potential for electricity production especially in Belgium due to weather conditions (Elia Group, 2017). The wind energy provides mechanical power through the wind turbine connected to an electric generator which generates electricity. However, to install wind farms, the number of appropriate places and places that are tolerated by the population is restricted. Nevertheless, there are still technology improvements enabling the deployment of cheaper, quieter, more flexible and efficient wind turbines. Wind energy combined with solar energy are seasonally and temporally complementary since available

wind power is usually high when solar power is low and inversely. Therefore, it can be considered as one same resource. Besides, the **energy efficiency** of wind turbines and solar panels is considered for both to be 100% as energy input cannot be measured and is unlimited. (Prussi, Yugo, De Prada, Padella, Edwards, et al., 2020b)

Other renewable energies are biomass, geothermal and hydropower but they only represent a minor part of current and future electricity generation in Europe and Belgium.

e) Natural gas

Natural gas is produced from dedicated fields or associated gas in oil fields. During extraction of the gas, which is primarily methane, other gases come out and contain inert gases including nitrogen and CO₂. The total **energy expenditure and GHG emissions** during extraction, processing and transportation vary depending on the origin. Transportation accounts for the biggest share of energy expenditure due to long distances. (Prussi, Yugo, De Prada, Padella, Edwards, et al., 2020b)

Natural gas is either supplied via underground and undersea pipelines or shipped in form of Liquefied Natural Gas (LNG) to Europe. For piped gas, distance increases energy requirement as pipelines need compression stations at regular stages, which consumes a part of imported gas. When distances are too large or there are no available pipelines, shipped LNG provides an alternative. Before being shipped, the extracted gas is being cleaned and liquified which requires extra electricity consumption (usually produced from the gas supply itself). During the processing and transportation of gas there is some CO₂ release and methane leakage. (Prussi, Yugo, De Prada, Padella, Edwards, et al., 2020b)

The Belgian network is connected with the majority of natural gas supply of the European market. In 2019, from the gas transported to Belgium 88% was piped gas mostly coming from Norway and the Netherlands. The other 12% were shipped LNG coming from Qatar and Russia. Natural gas is further distributed around the country through an extensive network of pipelines. (Fluxys Belgium & Fluxys LNG, 2021; FPS Economy, n.d.) Transfers between pipelines of different pressures also induce energy loss. (Prussi, Yugo, De Prada, Padella, Edwards, et al., 2020b)

Afterwards, natural gas can be transformed into electricity by two types of power stations, either with the Brayton cycle or the Combined cycle. The Brayton gas turbine cycle burns

natural gas producing a compressed gas which spins the blades of the steam turbine. The turbine is coupled with an electric generator, in which magnets start spinning and move electrons in the wires generating an electric current and, thus, produces electricity (Langston, 2014). This process has an average energy **efficiency** of 40% (Prussi, Yugo, De Prada, Padella, Edwards, et al., 2020b). When using a CCGT, besides burning gas to drive a turbine, combined cycle power plants use the wasted heat in order to boil water and produce steam that turns a second turbine, thus producing more electricity (Langston, 2014). As a result, combined cycle power plants increase the overall **efficiency** up to 60% and are, therefore, widely used in Europe. Even though conventional thermal steam cycles are still used, nearly all new capacities are and will be with CCGT. (Prussi, Yugo, De Prada, Padella, Edwards, et al., 2020b)

Moreover, natural gas, although being a fossil fuel, has a lower content in carbon than oil and coal making it more attractive to reduce CO₂ emissions. It is already used widely in Europe and its share is expected to increase to replace nuclear power and coal but also to guarantee security supply as electricity demand is growing. So, natural gas power plants have lower **GHG emissions** than coal and oil power plants because of the high efficiency of CCGT and because natural gas contains less carbon. Although it emits more GHG emissions than nuclear and renewable energies, it is cleaner than other fossil fuels and supports the transition to cleaner energy. (Prussi, Yugo, De Prada, Padella, Edwards, et al., 2020b)

Electricity transmission and distribution

Once the electricity is produced it needs to be distributed through transmission grids for consumption, causing power losses. After long distance transmission at High Voltage (HV)¹⁰ (to reduce losses), electricity is transformed to Medium Voltage (MV) to be distributed to different places of consumption like factories, urban areas, buildings, etc. Finally, Low Voltage (LV) electric energy is supplied to individual private users. (Prussi, Yugo, De Prada, Padella, Edwards, et al., 2020b) Since electricity transmission and distribution causes some power losses, the closer the electricity production is to the final consumer, the higher the energy efficiency.

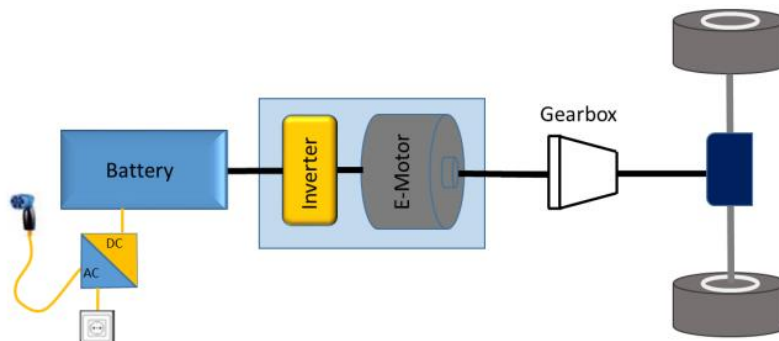
¹⁰ HV >36000 V; 1000V<MV<36000V ; LV<1000V

3.2.3.2. TTW: Powertrain

Battery electric vehicle (BEV)

The power of BEV is delivered by an electric motor, with a battery as energy storage (Figure 9). Because of the low energy density of batteries, electric trucks have a lower operating range and higher curb mass compared to conventional trucks. (Röck et al., 2020) BEV have an operating range between 350 km (Daimler Truck AG, 2021) and 450 km depending on driving profile (E-Force, 2021). Larger operating range would require more batteries, increasing the curb weight, and limiting the maximum payload. This aspect is estimated to improve in the future. (Campanari et al., 2009; Röck et al., 2020) The batteries used in the JEC TTW report v5 (2020) for the tractor-semitrailers are the Li-NMC (Lithium, Nickel, Manganese, Cobalt) technology reaching an energy density of 110Wh/kg and a pack capacity of 840 kWh. Moreover, as the battery is included in the powertrain, the BEV has the capacity of regenerative braking where negative mechanical power at the wheels (i.e. when braking) is regenerated into electrical energy and stored in the battery (Lombardi et al., 2020; Röck et al., 2020).

Figure 9: Topology of battery electric vehicles (BEV) (Röck et al., 2020, p. 27)



The JEC TTW report v5 (2020) models the BEV with a permanent magnet synchronous motor (PMSM) as traction motor. This type of machine presents the lowest weight and volume and the best efficiency amongst electric motors. The report considers a direct-current (DC) system for charging which is faster than alternating current (AC). In order to convert the batteries direct current, an inverter is required for the conversion into alternating current to power the PMSM. The e-motor (including PMSM electric motor and inverter) conversion efficiency, electrical-to-mechanical, is estimated to reach up to 92%. (Röck et al., 2020)

Energy losses while charging from grid into the battery also need to be considered in the TTW analysis. Long-Haul HDV usually need one fast charging per day. With high power charging (DC) losses of 7% as well as 7% of charging station losses, the JEC considers 86.5% charging efficiency.

Electric trucks can thus reach **powertrain-to-wheel efficiencies between 85% and 91%** (E-Force, 2021; IEA & OECD, 2017). Lombardi et al. (2020) defines this efficiency at 89.2%.

BEV produce no **GHG emissions** during vehicle operations and are therefore referred as “zero-emission”¹¹ vehicles. But these only consider TTW emissions and are not representative. The whole WTW analysis needs to be considered to assess the overall environmental performance of the fuel. (Lombardi et al., 2020; Röck et al., 2020)

3.2.3.3. WTW: Environmental performance

As the BEV do not produce tailpipe emissions, the GHG emissions on a WTW basis depend heavily on the electricity generation pathway. The carbon intensity of the electricity used to charge the trucks will therefore determine the overall environmental performance (IEA & OECD, 2017; Moro & Lonza, 2018; Rangaraju et al., 2015; Sen et al., 2017).

Concerning the energy efficiency, the total energy input required to generate 1MJ of electricity is different for each pathway. Because primary resources, when converted to electricity, do not have the same conversion efficiency (output electricity energy generated / input primary energy consumed) because of different efficiencies in the power plants. For thermal power stations, the conversion efficiency to transform natural gas or coal into electricity is 60% or below. For fossil energy, the primary energy input is calculated from the thermal energy content, the Lower Heating Value (LHV), of the fuel. For nuclear power and renewables, the input of energy cannot be computed based on LHV. For nuclear power plants, the efficiency is not determined by the energy input of the primary resource (uranium) consumed, but by a conventional thermal efficiency of the power plant. The JEC WTT report v5 (2020b), has estimated that for nuclear power plants 33% of primary energy is converted into electricity. While, for renewables the conversion efficiency is considered 100% as the input of primary energy cannot be precisely measured and is unlimited. Therefore, it is

¹¹ Except from fine particles formed by braking and wearing of the tires.

deemed that renewable energy is created from “nothing”¹². (Prussi, Yugo, De Prada, Padella, Edwards, et al., 2020b)

Despite low conversion efficiency of the electricity production mix it is counterbalanced by high on-board conversion efficiency of batteries. (Lombardi et al., 2020)

The best case scenario is thus when electricity is generated from renewables and produced near the final consumer. This solution offers nearly zero emissions and a small energy expenditure. (Lombardi et al., 2020)

3.2.4. Hydrogen

Hydrogen (H₂) is the lightest and most abundant element in the universe. The advantage of hydrogen is that it can theoretically be produced from nearly any primary energy source. It is, amongst other hydrocarbons, chemically bound with methane (CH₄) and water (H₂O) (Schlapbach, 2011). Nowadays, most of the hydrogen is produced through steam methane reforming and a small part by water electrolysis. Steam reforming of methane is widely used in the chemical and industrial industries and is called “grey hydrogen” since the process releases CO₂ emissions. However, if this process includes carbon capture it reduces CO₂ levels and it is called “blue hydrogen”. When hydrogen is produced by splitting water through electrolysis it refers to “green hydrogen” if the electricity used for the electrolysis is from a renewable source as it emits no direct GHG emissions. (CertifHy, 2021)

In a FCEV, the hydrogen is stored in a tank and is converted back to electricity, by means of fuel cells, to power the vehicle (IEA & OECD, 2017). It is worth noticing that thanks to electrolysis which converts electricity into hydrogen, and fuel cells which transform hydrogen back into electricity (despite energy losses), hydrogen provides a solution to store electricity, thus, dealing with the issue of intermittency of renewable energies. It would enable to match electricity demand and supply, by storing electricity when there is a surplus of renewable electricity and providing electricity to different end-use sectors when demand is high during off-peak periods. As a result, FCEV could complement a more renewable electrical energy system. (Compiègne & Peythieu, 2020; Smallbone et al., 2020)

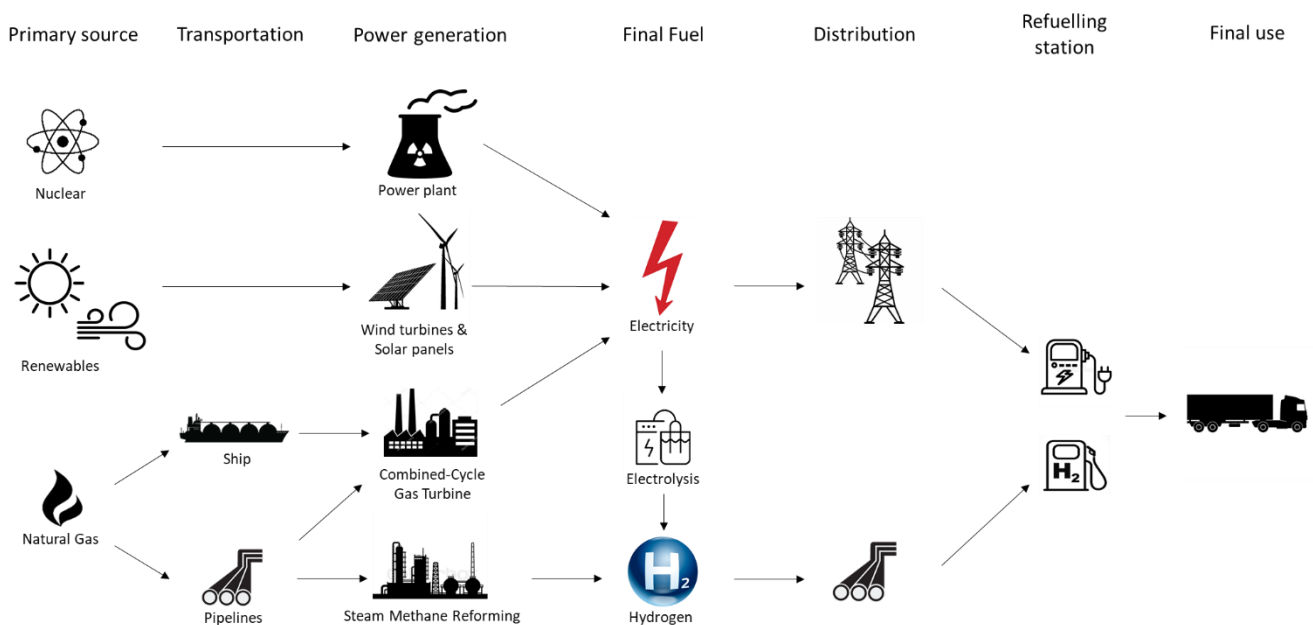
Fuel cell trucks present great potential thanks to the good energy efficiency and gravimetric energy density of hydrogen, allowing long operating ranges thanks to better autonomy.

¹² But the renewable electricity is limited by the available capacities.

However, the high volumetric energy density of hydrogen means it needs to be compressed to 35MPa or 70MPa¹³ to reduce the storage space (Prussi, Yugo, De Prada, Padella, Edwards, et al., 2020b).

Hydrogen is considered here as energy carrier to power FCEV. Its capacity to reduce GHG emissions will heavily depend on the hydrogen production pathway (IEA & OECD, 2017). Two main cases are analysed, the production of hydrogen by steam methane reforming and by electrolysis. For the steam methane reforming case, the pathway with natural gas as primary resource is discussed. For electrolysis case, the same production pathways as for electricity are used (Figure 10).

Figure 10: Production pathways for hydrogen



3.2.4.1. WTT: From primary energy resource to fuel

Hydrogen production

a) Natural gas: Steam Methane Reforming

Hydrogen can be produced from natural gas either directly through steam reforming or indirectly by electrolysis with electricity generated by natural gas. Here we discuss the first option. Hydrogen produced by steam reforming of methane is already a well-established and widely used process in refineries and petrochemical industries. (Lombardi et al., 2020; Prussi, Yugo, De Prada, Padella, Edwards, et al., 2020b) It is a high temperature process in which

¹³ 350 bar is currently used for heavy duty, and 700 bar for passenger cars.

methane (CH_4) reacts with steam (H_2O), in presence of nickel-based catalyst, producing a mixture of carbon monoxide (CO) and hydrogen (H_2), known as “syngas”. But carbon monoxide further reacts with the steam, referred as the “CO-shift”, and forms CO_2 and more hydrogen. (Office of Energy Efficiency & Renewable Energy, n.d.-b)

Currently, most world’s hydrogen is produced from steam methane reforming, and is referred to as “grey hydrogen”. Because this process results in higher **GHG emissions** per unit of energy than fossil-based fuels. The thermodynamic **efficiency** of steam reforming varies between 50% and 85%, with large-scale production facilities having the highest efficiency. (IEA & OECD, 2017) This means that after the process of steam methane reforming is completed, a share of methane remains unreacted. Also, the process requires full decarbonisation of the fuel to obtain pure hydrogen, which also produces concentrated CO_2 emissions, thus making it attractive for Carbon Capture and Sequestration (CCS). (Prussi, Yugo, De Prada, Padella, Edwards, et al., 2020b)

Carbon capture and sequestration

Carbon capture and storage techniques are gaining popularity as they avoid CO_2 release into the atmosphere (Prussi, Yugo, De Prada, Padella, Edwards, et al., 2020b). According to the European Commission (2018), the CCS can play a key role to reduce CO_2 emissions across many sectors as well as the production of low-carbon hydrogen. Hydrogen produced from steam methane reforming combined with CCS is referred as “blue hydrogen”. Although the carbon capture requires extra **energy**, it offers a scalable and viable solution to reduce relative **CO_2 emissions** of hydrogen production by 40% (Smallbone et al., 2020).

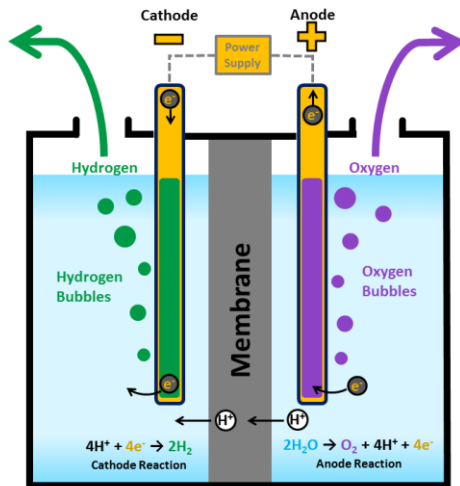
The captured CO_2 is stored in a place where it cannot enter the atmosphere, such as an underground geological formation. An alternative to storage is Carbon Capture and Utilization (CCU) where the captured CO_2 is reused as feedstock for other purposes.

b) Electricity: electrolysis

Another way to produce hydrogen is via electrolysis, a promising option for low-carbon or carbon-free hydrogen. Electrolysis is a process in which electricity is used to split water (H_2O) into oxygen (O_2) and hydrogen (H_2) (Figure 11). Electrolysis was already used a century ago to produce hydrogen for fertiliser production but was replaced by hydrogen produced from natural gas. Currently, water electrolysis represents less than 0.1% of hydrogen production in

the world. But with rise of renewable electricity and a decline in costs, hydrogen from electrolysis is gaining popularity and many projects with high electrolyser capacities are coming up. (IEA, 2020a)

Figure 11: Transformation of water to hydrogen by electrolysis (Office of Energy Efficiency & Renewable Energy, n.d.-a)



Hydrogen can be produced with electricity from various sources. As a result, the environmental performance of hydrogen will largely depend on the carbon intensity of the electricity used. Hydrogen produced with electricity from the grid, in countries with a high fossil-based electricity mix, will result in much higher **GHG emissions** than in countries with a high share of renewables or nuclear power in the electricity mix (Moro & Lonza, 2018; Rangaraju et al., 2015). Currently, hydrogen produced by electrolysis by the EU electricity mix requires more energy and emits more GHG than fossil fuels, whereas if powered by renewable energies (i.e. excess wind electricity capacity) it could provide a 83% reduction in CO₂ emissions (Smallbone et al., 2020).

Electrolysis plants can range from very small, for small-scale distribution, to very large scale, for central production facilities. The thermodynamic efficiency of hydrogen production varies between 65% and 80% (lab-scale) for electrolyzers (IEA & OECD, 2017) and it is not affected by scale but can vary depending on auxiliaries and operating pressure (Prussi, Yugo, De Prada, Padella, Edwards, et al., 2020b). On the market alkaline electrolyzers are available and recently large electrolyzers using proton exchange membranes (PEM) are being commercialized. It is expected that efficiency of electrolyzers will improve in the future, as lab-scale applications are already achieving 85% to 90% efficiency (IEA & OECD, 2017). The

JEC WTT report v5 (2020b), has defined a representative **energy efficiency** of 65% for all electrolysis, regardless of size and technology (alkaline, PEM).

Hydrogen transport and distribution

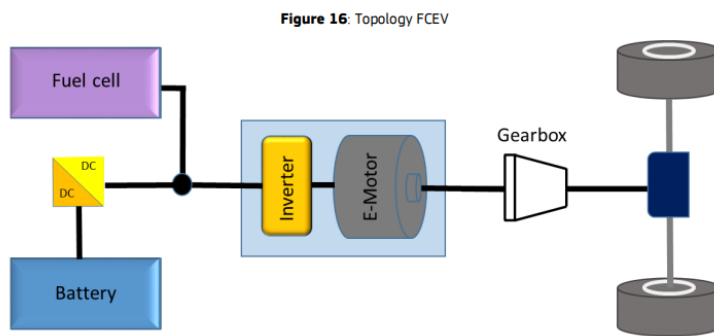
Once hydrogen is produced, it is at high pressure at electrolyser outlet and still needs to be compressed at 3MPa. In case hydrogen is produced in a central production facility, it can either be liquefied and transported by truck, or distributed via pipeline and further compressed for the refuelling station compressor inlet. In the case of an on-site electrolyser, hydrogen doesn't need to be transported and is available at maximum 3MPa outlet pressure. The compression and cooling of hydrogen after production and at refuelling station is energy intensive and contributes to the WTT emissions. (Prussi, Yugo, De Prada, Padella, Edwards, et al., 2020b)

3.2.4.2. TTW: Powertrain

Fuel Cell electric vehicle (FCEV)

The powertrain of a FCEV is similar to the BEV one, except that hydrogen is used as energy carrier and being converted into electricity through a fuel cell generator (Figure 12). The electrical energy powers the propulsion system. Here the battery, which is smaller than for BEV, acts as a buffer to cope with peak demand during acceleration, to lower the dynamics on the fuel cell to extend its lifespan, but also to recover brake energy. (Röck et al., 2020; Smallbone et al., 2020) Despite the smaller battery, FCEV include a hydrogen tank which takes up four times more space than a diesel tank due to the lower volumetric energy density of hydrogen. Besides, hydrogen need to be compressed to 35MPa or 70MPa to allow the same order of magnitude of operating range as conventional fuel, thus, high-pressure tanks are necessary. (IEA & OECD, 2017) A DC/DC converter is located next to the battery to optimise losses as less energy runs from the battery than from fuel cell to the electric motor. (Röck et al., 2020) The JEC TTW report v5 (2020) considers 2% losses from the converter.

Figure 12: Topology Fuel Cell Electric Vehicle (FCEV) (Röck et al., 2020, p. 31)



The Polymer electrolyte membrane (PEM) fuel cells has currently the highest potential to be used in vehicle application (IEA, 2020a; Ramachandran & Stimming, 2015). To evaluate the fuel cell system's efficiency, the electric output energy needs to be divided by the hydrogen input energy. To compute the energy content of hydrogen, the LHV is used. According to Lohse-Busch et al. (2020) with a LHV of 120 MJ/kg, the measured fuel cell system peak efficiency is 63.7%. The JEC TTW report v5 (2020), based on the same LHV, estimates current **powertrain-to-wheel efficiency of FCEV around 50%** and assumes it will be increased by 5% in 2025 (Röck et al., 2020). Lombardi et al. (2020) uses a 55% fuel cell efficiency.

3.2.4.3. WTW: Environmental performance

Currently, most world's hydrogen is produced from **steam methane reforming**. But this process results in greater GHG emissions per unit of energy than fossil-based fuels. However, because FCEV have no tailpipe emissions, and a higher efficiency of fuel cell batteries compared to conventional internal combustion engines it can compensate, leading to lower GHG emissions per km. Still, the WTW emissions of hydrogen from natural gas steam reforming being used as energy carrier for FCEV do not result in important reductions of GHG emissions compared to diesel for conventional trucks. (IEA & OECD, 2017) By including **CCS** in the hydrogen production pathway, Lombardi et al. (2020) results show an increase of primary energy consumption of 25%, but a decrease by 50% of GHG emissions.

Lee et al. (2018) shows in its study that producing hydrogen by electrolysis from **renewable energies** instead of central SMR pathway, reduces the fossil fuel consumption by 90% and thus GHG emissions by 86% on WTW basis. However, a lot of energy is still needed in the WTT process because of high energy requirements from electrolysis and compressing.

Then in the case of hydrogen produced by electrolysis from the **electricity mix**, several studies point out the key role of the carbon intensity of the mix. Gustafsson et al. (2021) show that hydrogen through SMR requires less electricity than electrolysis, thus, achieving lower GHG emissions in case the electricity mix has a high share in fossil energies. Results depict that when the electricity mix has a carbon intensity higher than 250 g CO_{2eq}/kWh, which is quite low from an international perspective, the hydrogen produced from the electricity mix will have higher WTW emissions than when produced from SMR. Further, the Carbon 4 report (2020) claims that producing hydrogen from the average EU electricity mix should be excluded as it leads to higher WTW emissions than conventional ICEV.

Overall, hydrogen already reaches high TTW efficiency but the upstream efficiency of WTT need to be improved. Indeed, energy losses result from several stages during the production, transportation, and refuelling. Consequently, the production has to shift to a low-carbon pathway. (IEA & OECD, 2017)

3.3. Comparison of the environmental performance between Diesel ICEV, BEV, FCEV

To assess the environmental performance of a fuel/ energy carrier, based on Well-to-Wheels (WTW) approach, the evaluation of both the energy efficiency and GHG emissions are relevant indicators as they reveal which solution implies fewer primary sources exploitation and which solution provides the biggest contribution to GHG emission reductions. Although, a solution offers an advantage in terms of GHG emissions, it might have a worse energy efficiency or the other way around.

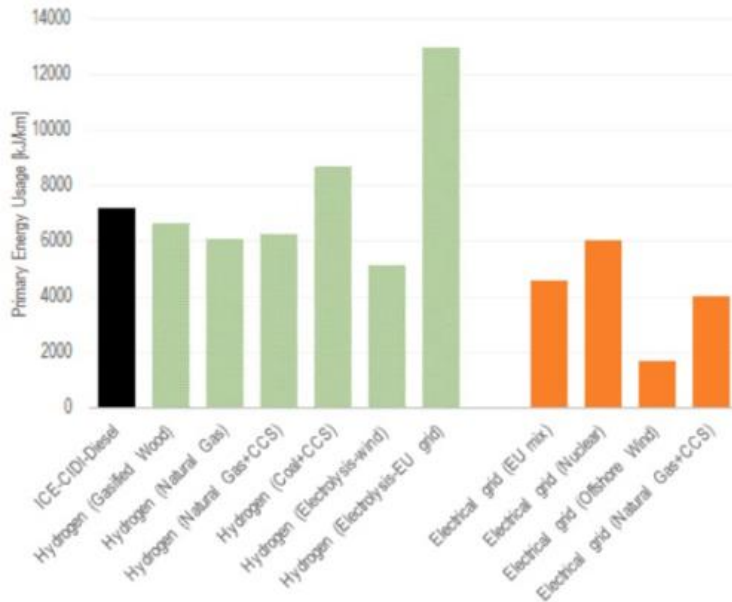
3.3.1. Energy efficiency

If we compare energy consumption of the 3 fuels/energy carriers, researches show that, regardless of the pathway, on a Well-to-Tank (WTT) basis BCEV and FCEV have a higher primary energy usage than diesel ICEV, because of low conversion efficiencies from electricity production mix (Lombardi et al., 2020). However, BEV and FCEV reach much higher Tank-to-Wheels (TTW) energy efficiencies, respectively about 85% and 50%, compared to diesel engines with up to 30% efficiency (IEA & OECD, 2017; Lombardi et al., 2020; Röck et al., 2020; Smallbone et al., 2020).

On a WTW basis, Smallbone et al. (2020) study shows that electric HDV, regardless of their primary energy source, achieve higher energy efficiencies than hydrogen and diesel trucks.

Also, hydrogen trucks are requiring less primary energy than diesel trucks, except for hydrogen by electrolysis with EU electric mix which is more energy intensive (Figure 13).

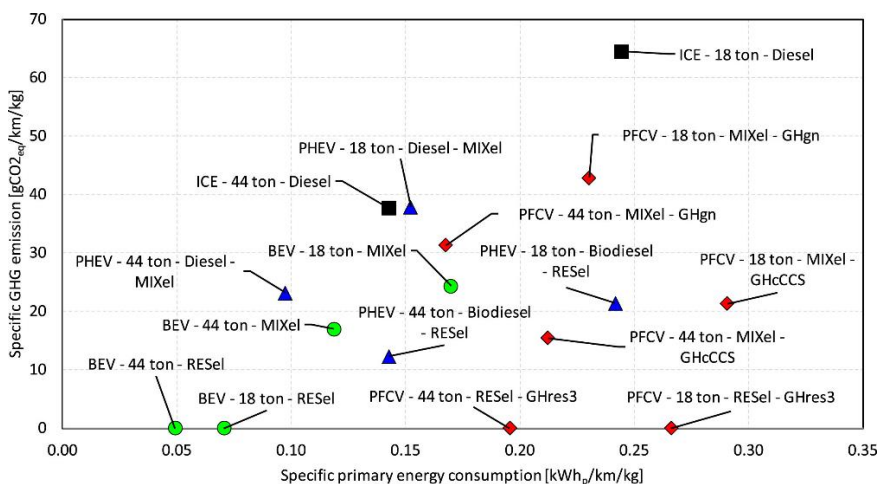
Figure 13: Sensitivity analysis showing the impact in terms of primary energy usage (kJ/km) of alternative fuel sources (Smallbone et al., 2020, p. 18)



(a) Sensitivity to primary energy usage

Lombardi et al. (2020) is in line with the fact that electric trucks are the most energy efficient on a WTW basis. However, the results for hydrogen trucks are opposite, depicting a higher primary energy consumption for all hydrogen production scenarios compared to conventional diesel ICEV. FCEV (44 ton) are indicated by a red square and diesel ICEV (44 ton) by black square on Figure 14.

Figure 14: Specific primary energy consumption and specific GHG emission for the 18 and 44 ton vehicles, sized for a driving cycle (Lombardi et al., 2020, p. 12550)



It is important to note that the FCEV, whether fuelled with hydrogen from SMR or electrolysis, will always require more energy than BEV. Because hydrogen produced from natural gas, besides the energy intensive SMR process, still requires electric energy to be compressed after production and at refuelling station (Lee et al., 2018). While, hydrogen produced from electricity suffers from energy losses during electrolysis (~35% loss), which turns electricity into hydrogen, and again when converted back to electricity power through fuel cells (20-35% loss) for propulsion (IEA & OECD, 2017; Prussi, Yugo, De Prada, Padella, Edwards, et al., 2020b; Ramachandran & Stimming, 2015). Despite energy losses, hydrogen presents a great potential to store electricity and therefore a solution to store excess power from renewable energies. "Green" hydrogen can then be used to power vehicles, although electricity available from renewable peak power may not be sufficient to produce a significant share of the hydrogen needs (Ramachandran & Stimming, 2015). It is claimed that hydrogen from renewable electricity is still not likely in the near future as renewable electricity first need to replace the current fossil-based electricity consumption (electrification before hydrogen production, since it is more efficient) (Calvo Ambel et al., 2017; Ramachandran & Stimming, 2015).

Although FCEV require more energy than BEV, the energy density of hydrogen storage and total weight of the power train do present an advantage compared to electric batteries, making them more suitable for long-distance transportation (Ramachandran & Stimming, 2015). Hydrogen is still having lower energy density than diesel, but technology improvements will make both hydrogen and electric powered vehicles competitive on gravimetric and volumetric density in the coming decade (Ramachandran & Stimming, 2015; Smallbone et al., 2020).

3.3.2. GHG emissions

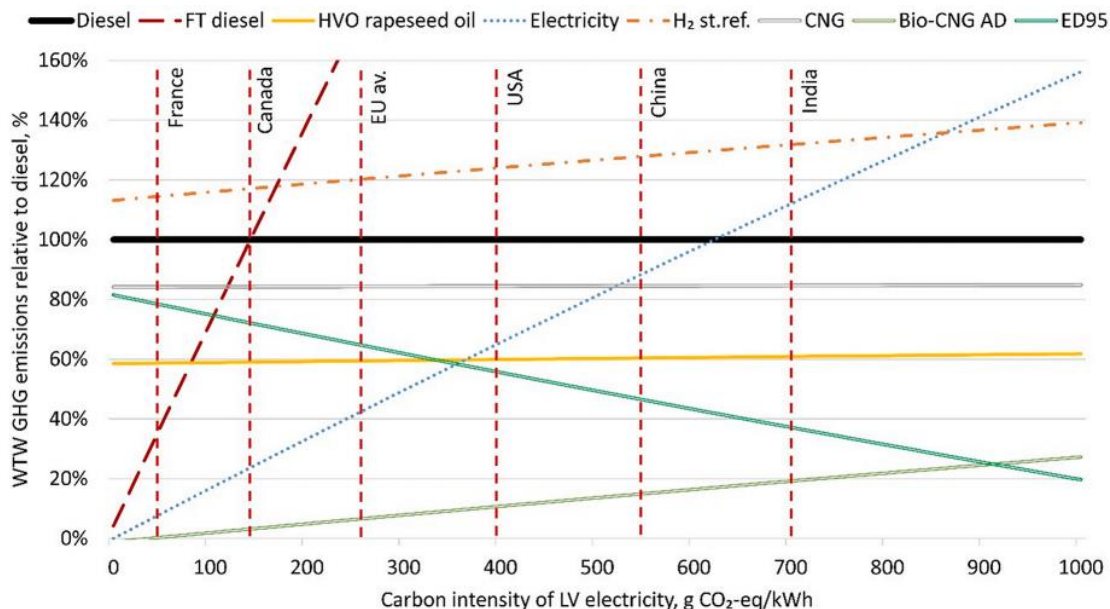
BEV and FCEV have a different structure of WTW GHG emissions than conventional diesel trucks. For conventional diesel trucks the tailpipe exhaust GHG emissions represent the biggest share, due to low efficiency of ICE. Whereas, for BEV and FCEV the major GHG emission source is from the production of the electricity and hydrogen, while they present no tailpipe emissions. Therefore, the carbon intensity of the electricity system is determinant for the environmental impact of energy carriers with a high electricity dependence. (Amant et al., 2020; Gustafsson et al., 2021; Ramachandran & Stimming, 2015; Rangaraju et al., 2015; Smallbone et al., 2020)

Several studies have already been conducted to assess the GHG emissions of different fuels based on a WTW analysis. Although results are often similar, sometimes different conclusions are drawn, as seen earlier by the figure of Smallbone et al. (2020) and Lombardi et al. (2020).

From the literature it is clear that **BEV** powered by electricity from the **EU mix** provide significant reductions in GHG emissions compared to conventional vehicles (Amant et al., 2020; Lombardi et al., 2020; Ramachandran & Stimming, 2015; Rangaraju et al., 2015; Sen et al., 2017). According to Gustafsson et al. (2021), a 40-ton long-haul electric truck, with EU average electricity, emits 60% less GHG than a diesel truck on a WTW basis (Figure 15). The lower the carbon intensity of the grid, the lower the GHG emissions and in case the electricity is generated from a **renewable source**, the WTW GHG emissions are zero (Gustafsson et al., 2021; Lombardi et al., 2020). Rangaraju et al. (2015) studied the Belgian case where, thanks to a high nuclear share in the electricity mix, BEV present much lower life-cycle GHG emissions than its diesel powered counterpart.

Figure 15: Well-to-wheel greenhouse gas emissions (relative to diesel) of energy carriers for a 40-ton long haulage truck, as a function of the carbon intensity of the electricity system (Gustafsson et al., 2021, p. 7)*

*note: FT diesel = Fischer-Tropsch diesel; HVO = Hydrogenated vegetable oil; H₂ st. rfe. = hydrogen from steam methane reforming; CNG = Compressed Natural Gas; Bio-CNG AD = methane produced through anaerobic digestion; ED95 = ethanol



According to Gustafsson et al (2021), in the case of **hydrogen** produced by **electrolysis with the EU electric mix**, because of the low conversion efficiencies, GHG emissions are so large that they offset the benefits of replacing fossil diesel. The Carbon 4 report (Amant et al., 2020), based on a life-cycle analysis, confirms that semi-trailer trucks running on hydrogen by

electrolysis with EU electric mix results in higher carbon footprint than the conventional ICEV. However, in a country with a low carbon intensity of the electricity mix such as France, the footprint of FCEV is smaller than conventional ICEV but remains twice as large as the BEV.

The Carbon 4 report also studies FCEV from **renewable energy electrolysis** and even when taking into account the vehicle carbon footprint, this solution presents lower GHG emissions than conventional trucks. Lombardi et al. (2020), considers that hydrogen from renewable energy electrolysis based on a WTW analysis, have zero GHG emissions but, as discussed earlier, hydrogen production requires more energy because of the conversion steps. However, in this case the extra energy required, does not mean that a higher number of actual resources will be consumed as energy comes from an unlimited resource, but it means that larger investments to cover the electricity demand are needed. As mentioned before, capacities to produce electricity from renewable energy are currently limited and first need to replace the existing fossil-based electricity mix (Ramachandran & Stimming, 2015).

Concerning **hydrogen from SMR**, Gustafsson et al. (2021) point out that it has a lower carbon footprint than hydrogen by electrolysis with carbon intensive electricity. The study also shows that hydrogen from SMR generates higher GHG emissions than diesel, regardless of the electricity mix (Figure 15). On the contrary, several studies show that hydrogen from SMR has lower life-cycle GHG emissions than diesel trucks (Amant et al., 2020; Lee et al., 2018; Lombardi et al., 2020) but still higher than BEV (Ramachandran & Stimming, 2015). Nevertheless, this fossil natural gas steam reforming remains highly emitting and does not reduce GHG significantly (Amant et al., 2020). Consequently, the option of **carbon capture and storage** (CCS) offers a viable solution to reduce considerably GHG emissions from this pathway. According to Lombardi et al. (2020) CCS although it increases energy expenditure by 25%, it allows to halve the GHG emissions.

To conclude, currently BEVs have the highest potential to reduce the environmental impact of road freight transportation. However, they still face limitations in terms of operating range, new infrastructure, and heavy reliance on decarbonisation of electricity generation. For larger distances, the higher energy storage densities of hydrogen (under high pressure) compared to batteries are favourable offering larger autonomy. (Ramachandran & Stimming, 2015) Besides, previous research show that energy carriers that rely heavily on electricity are not automatically preferable to diesel on a WTW basis. To reduce the carbon impact of the

transport sector, it is not sufficient to switch to electricity if the carbon intensity of the electricity grid is not improved in the first place. (Gustafsson et al., 2021) Globally, the phase out of nuclear power has not been compensated by the increase in renewable energy capacity but by fossil power plants. Since the world's electricity demand grows, the reliance on fossil fuels for electricity generation will increase, further increasing the carbon footprint of electricity generation. (Ramachandran & Stimming, 2015)

4. Results

In this chapter results from the WTW analysis are presented and broken down. First, general observations from the analysis are put forward. Secondly, the results are discussed according to each available primary energy source. The energy expenditure (kWh/km) and GHG emissions (g CO_{2eq}/km) are evaluated from a WTW perspective. Then, an overall comparison is drawn between the different energy carriers to measure their relative environmental performances. Finally, a sensitivity analysis is conducted to assess the environmental performance of the energy carriers with the Belgian electricity mix.

4.1. General observations

Figure 16 displays the WTW results in terms of GHG emitted expressed in “g CO_{2eq}/km” for each pathway. Results are organised according to vehicle powertrain technology (FCEV, BEV, ICEV) and production pathways of corresponding fuel/ energy carrier. For instance, “(FCEV) wind” represents here the WTW results for a truck powered by hydrogen, which is produced by electrolysis with wind energy. For each vehicle category, pathways are classified from lowest carbon footprint to highest carbon footprint. Figure 17 presents the WTW results in terms of energy expended expressed in “kWh/km” for each pathway keeping the same order of pathways as previous graph.

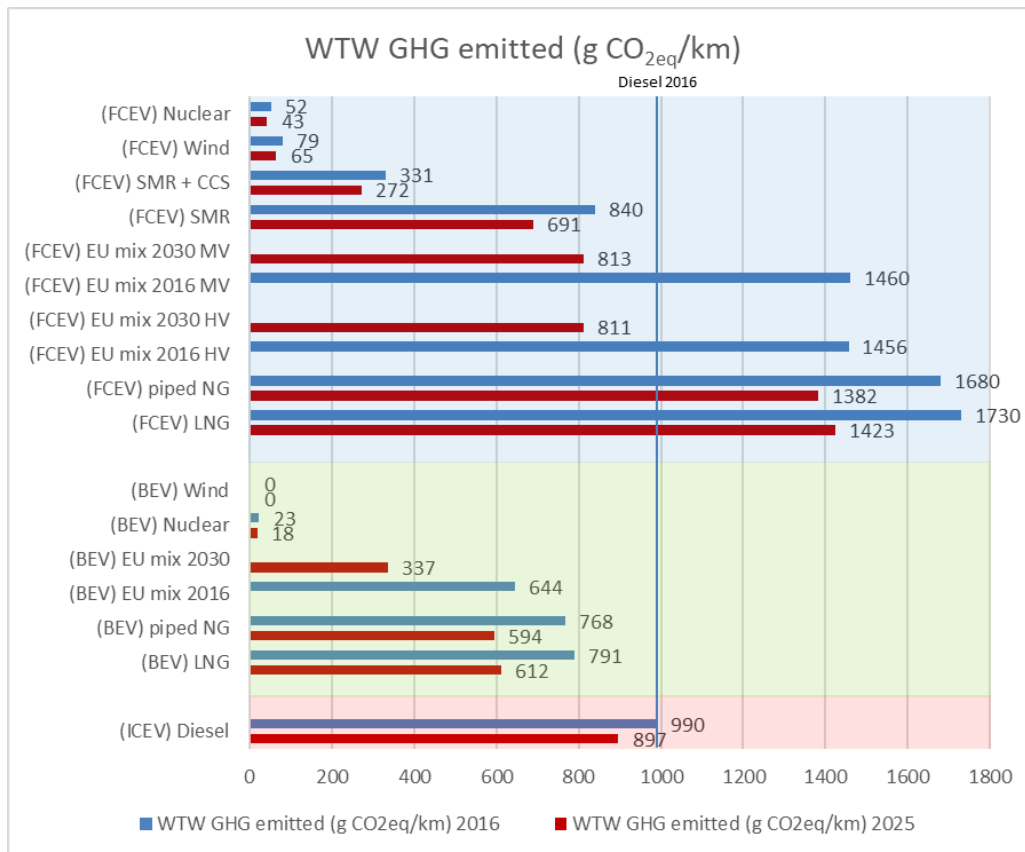
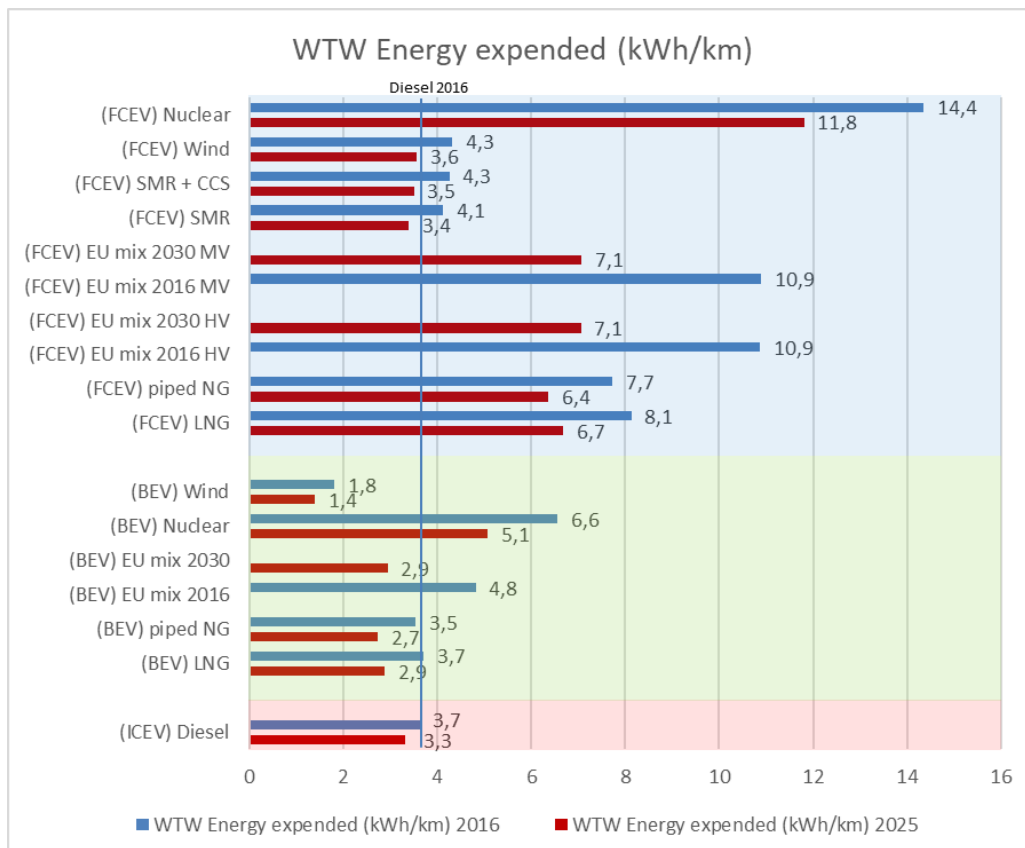
Figure 16: Well-to-Wheels greenhouse gas emitted (g CO₂/km) for investigated pathways

Figure 17: Well-to-Wheels energy expended (kWh/km) for investigated pathways



Before analysing each individual pathway, some general observations are worth mentioning.

First, when comparing both graphs we observe that several pathways, offering an advantage in terms of GHG emissions, do not systematically provide energy efficient solutions.

Secondly, it is clear from the graphs that for pathways with renewables, the energy expended is low and GHG emissions are nearly zero since there are virtually no emissions from well-to-tank and BEV and FCEV produce no tailpipe emissions.

Further, it is quite striking that for FCEV powered by hydrogen from electrolysis, the energy expended and GHG emissions are doubled compared to BEV. This is due to energy losses during electrolysis, which turns electricity into hydrogen, and again when converted back to electricity through fuel cells in the truck.

Lastly, between 2016 and 2025, performances improve thanks to higher efficiencies of vehicles. In this time horizon, diesel ICEV reduce energy expenditure and CO_{2eq} emissions by 9%, BCEV by 23% and FCEV 18%. For the EU mix pathways, the lower carbon intensity of the electricity mix significantly contributes to further cut down.

4.2. Nuclear

Nuclear power is used to generate electricity, which can either be used as a fuel for BEV or to produce hydrogen by electrolysis, which will power FCEV. From an energy point of view nuclear pathways are energy intensive, with 6.6 kWh/km of energy expended by BEV and 14.4kWh/km by FCEV, in 2016. Because of the low thermal efficiency (33%) of nuclear power plants, a lot of energy is lost during the process. Consequently, here the diesel ICE pathway presents lower energy consumption with 3.7 kWh/km in the same year. Moreover, the nuclear reactions generate radioactive waste giving rise to ethical and environmental debates.

Nevertheless, on a WTW basis in terms of GHG emissions, electricity and hydrogen produced from nuclear power offer low levels of CO_{2eq} emissions, 23.4 g CO_{2eq}/km and 51.7 g CO_{2eq}/km respectively. The only considerable GHG emissions are occurring upstream during mining, transport, and enrichment of the uranium and for the maintenance of the nuclear reactors.

So, considering the nuclear energy source, the hydrogen pathway with electrolysis on site, requires about double the amount of energy and emits about double the amount of GHG emissions compared to electricity. Consequently, here a BEV is a favourable alternative.

4.3. Wind

Wind power is a clean source of energy to generate electricity. If electricity is used directly to power BEV, in this pathway no GHG emissions are emitted, from a WTW perspective, as it does not consider construction of wind turbines. Besides, the energy expenditure is lower (1.8 kWh/km) than diesel ICEV (3.7 kWh/km).

If the renewable electricity is used to produce “green” hydrogen in a central electrolyser, GHG emissions of FCEV (79.2 g CO_{2eq}/km) are very low compared to diesel ICEV (990 g CO_{2eq}/km), but higher than BEV, because here the assumption is made that some electricity from the grid is used for compression. In terms of energy expended, the pathway electricity-to-hydrogen-to-electricity suffers from a low efficiency leading to double the amount of energy consumed compared to BEV and even exceeding diesel ICEV energy expenditure. However, in this case the extra primary energy required is wind, since this energy is unlimited, the actual primary resource can be consumed indefinitely. So, it rather implies that larger investments and resources need to be gathered to grow capacity, to build wind farms, to cover electricity demand.

In the case of renewables, BEV present the best environmental performance since they use available renewable energy more efficiently and emit no GHG emissions. FCEV still present a viable solution to reduce GHG emissions although it requires more energy.

4.4. Natural gas

Natural gas is either supplied via pipelines or shipped as LNG. It is a fossil energy source which can be used for electricity generation. The electricity can be used as fuel to power BEV or used to produce hydrogen by electrolysis to power FCEV. For both BEV and FCEV, the pathway with gas supplied via pipelines and the pathway with shipped LNG present similar results with a slightly higher energy expenditure and CO_{2eq} emissions (5%) for LNG because of liquefaction process. Here again the BEV presents much better environmental performance compared to FCEV. But natural gas can also be transformed directly into hydrogen through SMR, referring to “grey” hydrogen. This process produces hydrogen in a more efficient and less emissive way than with electrolysis from EU mix. Hydrogen through SMR does not reduce GHG emissions

considerably but can be combined with carbon capture technologies, referring to “blue” hydrogen, which despite a small energy penalty, reduces the CO_{2eq} emissions by 60%.

To sum up, considering the different natural gas pathways, FCEV fuelled with hydrogen produced from SMR combined with carbon capture, “blue” hydrogen, offers the best environmental performance. Despite a slightly higher energy expenditure (4.3 kWh/km) than BEV with piped NG (3.5 kWh/km) and diesel ICEV (3.7 kWh/km) it is compensated by the much lower carbon footprint and cuts down GHG emissions by two third compared to conventional trucks. Moreover, efficiencies of SMR and CCS improve by 2025, reducing this energy expenditure gap.

4.5. EU mix

Combining all previously mentioned primary resources we obtain the EU electricity mix. The share of primary sources changes between 2016 and 2030 (Figure 6). Electricity from the grid can be either used as fuel to power BEV or as energy carrier to produce hydrogen by electrolysis.

2016

It is clear from the graph that BEV offer much better environmental performance than FCEV when electricity from the grid is used as resource. Hydrogen from electrolysis with the EU electricity mix has to be disqualified as it produces ridiculously high amounts of GHG emissions and consumes a lot of energy. Also, from the JEC data it seems that hydrogen by electrolysis on site is slightly more emissive than when produced in central electrolysers and transported to the market by pipelines, because of power losses during the electricity distribution at MV.

BEV powered with electricity from the grid, despite consuming 1 kWh/km more than diesel ICEV, they provide a GHG emission reduction of 35% compared to the conventional trucks.

2030

By 2030, energy expenditure and GHG emissions fall thanks to a lower carbon intensity of the EU electricity mix. In 2030, BEV and FCEV with electricity from the grid consume one third less of energy and emit about half of GHG emissions compared to 2016 trucks. Nevertheless, FCEV remain energy intensive and end in meaningless lower CO_{2eq} emissions compared to diesel ICEV. Concerning BEV, GHG emissions are further reduced, providing 60% less emissions than conventional diesel trucks. Additionally, energy consumed by BEV is also lower.

In conclusion, considering the average EU electricity mix estimated in 2030, BEV provide a fairly good solution to cut down GHG emissions. For countries with an average carbon intensity lower than the EU this solution will provide further benefits. On the contrary, if the electricity mix is mainly fossil-based, this will lead to the opposite effect.

4.6. Cumulative results

Finally, the overall environmental performance of the fuels/ energy carriers is presented, for 2016 (Figure 18) and 2025+ (Figure 19), in terms of total energy consumed and GHG emitted. Both indicators need to be considered as it exposes which solutions require fewer primary resources exploitation and if they provide significant GHG reduction solutions. On the graph all energy carriers located in the left bottom corner show the best performance as energy expended and GHG emissions are low.

Figure 18: Well-to-Wheels environmental performance in terms of energy consumption and GHG emissions in 2016

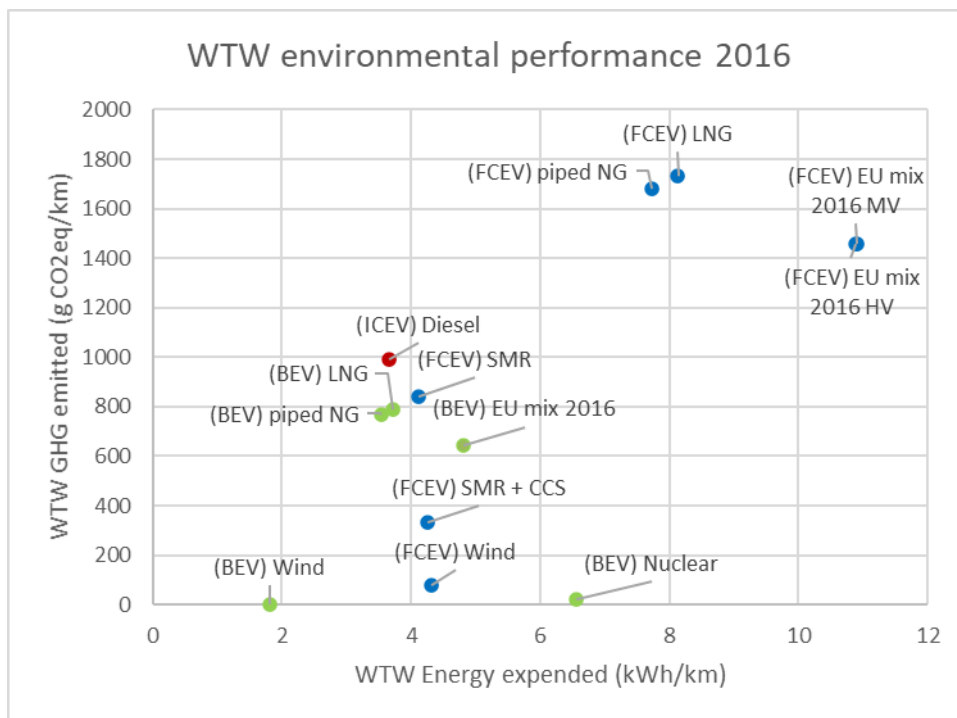
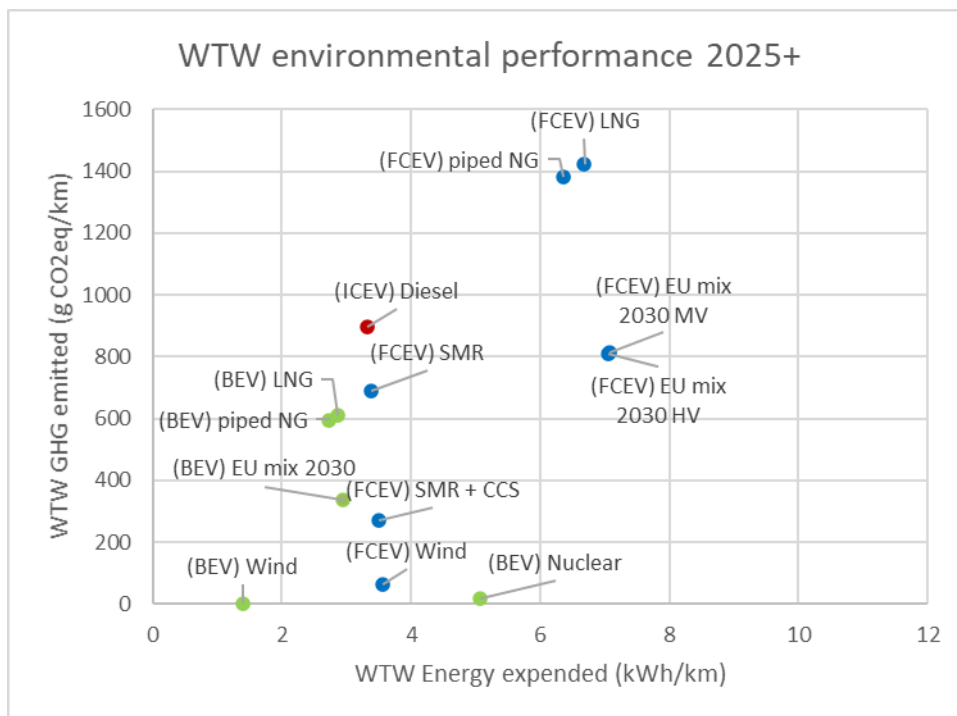


Figure 19: Well-to-Wheels environmental performance in terms of energy consumption and GHG emissions in 2025+



The results highlight that **BEV powered with renewable electricity** are the best performers, with no GHG emissions and low primary resources consumption. It is followed by **FCEV powered by “green” hydrogen**, although it requires more energy due to losses in electrical conversion, the very low GHG emissions compensate for it. Then, the option of **FCEV with “blue” hydrogen** (from SMR with carbon capture), despite a small energy penalty, presents a great potential in terms of GHG emissions with 67% reduction compared to conventional trucks. Lastly, **BEV powered by the EU electricity mix**, can be considered as a viable alternative, with an even greater potential for 2030. Other options like FCEV powered by “grey” hydrogen are considered as less relevant to significantly reduce the environmental footprint.

4.7. Sensitivity analysis: BE mix

In this section a sensitivity analysis is carried out to explore the potential of alternative energy carriers when the Belgian electricity mix is considered. The electricity production mix in 2020 is based on data gathered by Elia (2021) and the electricity mix in 2030 represents the predictions from Elia’s (2017) “base case” scenario. This scenario is “the minimum that has to be achieved to reach the EU 2030 targets” (Elia Group, 2017). Figure 20 illustrates the BE electricity production mix in 2020 and the projections for 2030. It is observed that the share

of renewable energy increases by 12%, the share of natural gas increases by 11% and there is a 16% increase of imported electricity form neighbours.

Figure 20: BE electricity production mix 2020 and prediction for 2030

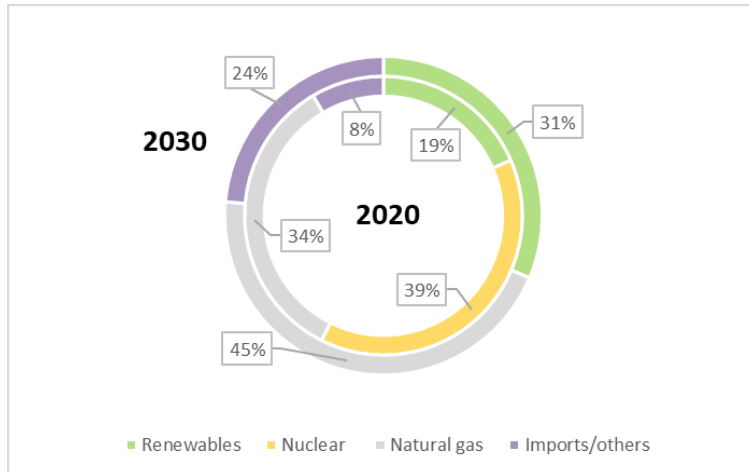


Figure 21 displays the WTW results in terms of GHG emitted, expressed in $\text{gCO}_{2\text{eq}}/\text{km}$ for the most relevant pathways. Results are organised according to vehicle powertrain technology (FCEV, BEV, ICEV) and production pathways of corresponding fuel/ energy carrier. For each vehicle category, pathways are classified from lowest carbon footprint to highest carbon footprint. Figure 22 presents the WTW results in terms of energy expended expressed in kWh/km for each pathway keeping the same order of pathways as previous graph.

Figure 21: Well-to-Wheels greenhouse gas emitted (g CO₂/km) including Belgian mix pathways

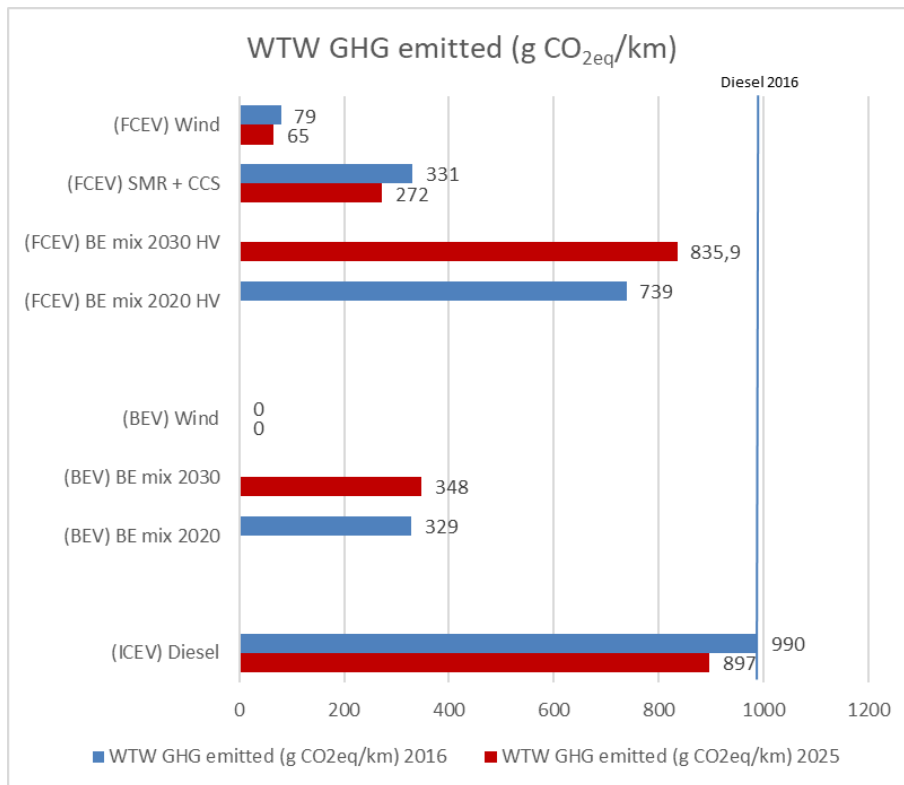
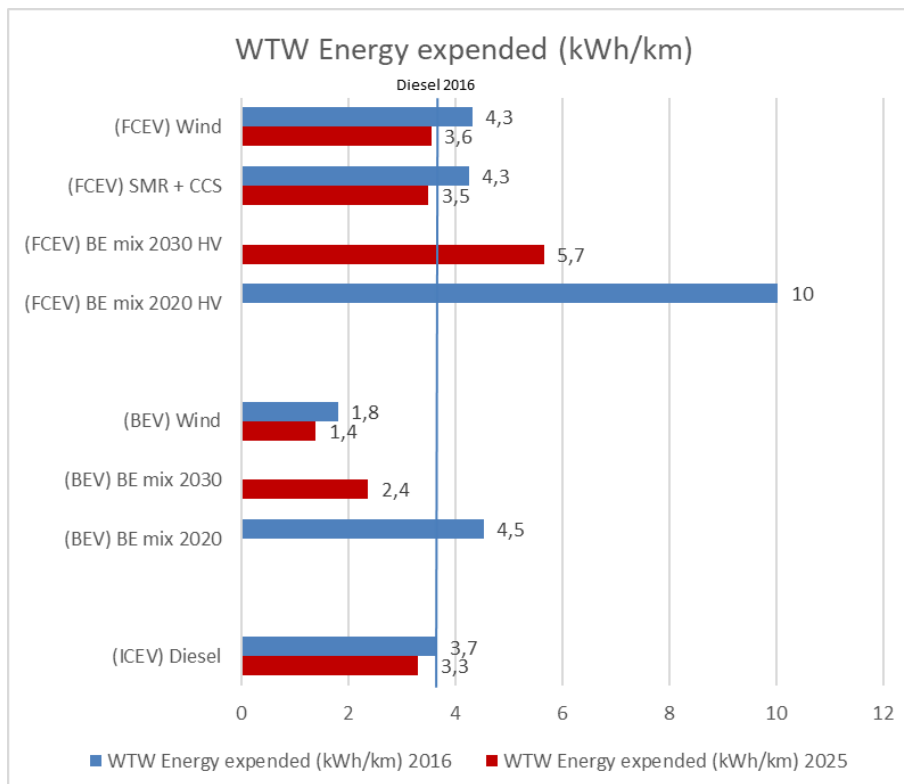


Figure 22: Well-to-Wheels energy expended (kWh/km) including Belgian mix pathways



2020

The 2016 EU average mix, studied earlier, has still a 20% share of electricity produced with coal, making it more carbon intensive than the 2020 BE mix studied here. As a result, the battery electric trucks and hydrogen powered trucks using electricity from the grid upstream, have a lower carbon footprint in Belgium.

However, for FCEV powered by hydrogen from electrolysis with the BE mix, the GHG emissions are only one quarter lower than diesel ICEV, whereas energy expended is 60% higher. Thus, GHG emission reductions are not sufficient to compensate for the very high energy requirements compared to diesel ICEV. Besides, “blue” hydrogen (SMR + CCS) and “green” hydrogen remain more performant.

Considering BEV powered by electricity from the Belgian grid, this option reduces GHG emissions by two third compared to conventional diesel trucks which compensates for the slightly higher consumption of energy. BEV with green electricity remain the most environmental friendly solution.

2030

The BE electricity mix in 2030, because of the nuclear phase out, ends up with a higher carbon intensity. The 39% share of electricity produced by nuclear power are replaced by a higher share of renewables, natural gas, and imported electricity from neighbours. This has an impact on the environmental performance of trucks running on energy carriers with high electricity dependence. On one hand, the FCEV and BEV have a slight increase of their carbon footprint, and, on the other hand, the energy efficiency improves. Results thus reflect a decrease of nuclear power, as this energy provides low GHG emissions but requires much energy. As a result, FCEV with hydrogen produced by electrolysis with the BE mix, remain an excluded option. The BEV powered with the BE electricity mix, despite a slight increase of GHG emissions compared to 2020, they remain significantly lower than diesel trucks, as well as the energy efficiency which has improved due to decrease in nuclear share and technologies advancements.

Overall, both BEV and FCEV powered, directly or indirectly, with **renewable electricity** prevail as the best solution with a considerable advantage for BEV. In case renewable sources are not available and the BE electricity mix is used as energy carrier, BEV offer a viable solution whereas FCEV should rather be fuelled with “blue” hydrogen.

5. Discussion

In this chapter the results of the case study are compared with other research¹⁴ from the literature, to confirm findings. After comparing the environmental performance of alternative energy carriers, it is necessary to take a step back and adopt a broader approach. It will allow to take into consideration the advantages and disadvantages of current technological solutions, that impact the decision-making of companies when making trade-offs. Therefore, other aspects than energy use and GHG emissions need to be addressed.

5.1. Results discussion

Overall, the results of the case study are in line with the literature, the highlights are mentioned in this paragraph. First, it is largely agreed that **BEV** prove to be the most energy efficient solution (Lombardi et al., 2020; Smallbone et al., 2020) and present great potential to reduce GHG emissions (Amant et al., 2020; Lombardi et al., 2020; Ramachandran & Stimming, 2015; Rangaraju et al., 2015). The case study showed that, electricity to power the truck should either be generated from renewable energy sources or sourced from the grid. It was demonstrated that, from a Well-to-Wheels (WTW) perspective, when electricity is produced from renewable energy sources, the GHG emissions are zero. This is in accordance with results from Gustafsson et al. (2021) and Lombardi et al. (2020). For BEV powered by electricity from the grid, the carbon footprint of this solution depends on the carbon intensity of the electricity mix. When the average EU electricity mix is considered, GHG emissions are significantly reduced compared to conventional diesel trucks. In the case study, GHG emissions are 35% lower in 2016, and 60% lower in 2030. Gustafsson et al. (2021) account already a 60% reduction of emissions, in 2020, compared to diesel trucks. Through the sensitivity analysis, it was computed that the GHG emissions of BEV, driven by the Belgian electricity mix in 2020, are already two third lower than the conventional diesel trucks, due to a high nuclear share in the mix. This is comparable to the results shown in the work of Rengaraju et al. (2015). In light of the nuclear phase out, the assumption was made that there would be zero nuclear power in the electricity mix by 2030. As a result, for BEV the tendency is reversed, with a slight increase of their carbon footprint, meanwhile remaining a viable solution. Further, Lee et al. (2018), Lombardi et al. (2020), and Ramachandran and Stimming (2015) confirm that **FCEV** with hydrogen from electrolysis, require more energy than BEV, due

¹⁴ mentioned in chapter 2.3. of the literature review

to energy losses during conversion from electricity-to-hydrogen-to-electricity and thus are more emissive. In case hydrogen is produced by electrolysis, it should be “green”, with electricity from renewable energy sources. In this study, green hydrogen presents very low WTW GHG emissions, with only some emissions accounted for compression, while Lombardi et al. (2020), account zero emissions. Then, in case hydrogen is directly produced from natural gas, it should be “blue”, in other words, by steam methane reforming (SMR) combined with carbon capture and storage (CCS). Results for blue hydrogen in this study present a decrease by two third of GHG emissions compared to diesel, while they are rather halved in the study of Lombardi et al. (2020). For “grey” hydrogen, produced by SMR without carbon capture, in the case study, GHG emissions are 15% lower than diesel but with higher energy consumption. Whereas, according to Gustafsson et al. (2021), grey hydrogen results in higher GHG emissions than diesel. Anyways, this option is not considered relevant to reach significant GHG emission reductions. To sum up, results may differ slightly due to different considerations in the calculations but lead to the same conclusions. Also, final figures were reviewed and approved by engineers from Colruyt Group¹⁵ and a mechanical-electrical civil engineer, Serge Vanhalme. Therefore, findings from this study can be considered correct.

5.2. Further discussion

Generally, BEV and FCEV are called “zero-emission” vehicles since they emit no tailpipe emissions. Nevertheless, from a WTW perspective, emissions will be zero or not, depending on the primary resource used to produce the energy carrier. Indeed, if only renewable energy sources are used it will result in zero emissions (without considering manufacturing of wind turbines or solar panels). But if other energy sources are used, such as natural gas or for the Belgian electricity mix, emissions can result far from zero in the upstream chain. However, regardless of production pathways, thanks to zero tailpipe emissions, BEV and FCEV are contributing to cut down local GHG emissions and air pollution. It is worth noticing that companies using vehicles in their fleet for distribution, are only held accountable for the GHG emissions from the use of the final fuel in the vehicle. As explained in section 3.1.3., companies account for and report for direct emissions in scope 1 and 2. The GHG Protocol (2011) requests companies to report on emissions produced by the combustion of fuels from

¹⁵ Colruyt has approved the numbers, however discussions and conclusions are only based on the writer’s opinion (Manon Schoevaerdt)

owned vehicles, meaning the upstream production pathway of fuels is not included. So, companies might only consider tailpipe emissions, which is zero for both BEV and FCEV, regardless of their primary energy source. Even though, in terms of GHG emissions, BEV and FCEV could be considered on the same level, hydrogen still requires more energy to be produced and is thus more costly than electricity.

While the environmental aspect cannot be neglected anymore, when companies decide to switch from diesel conventional trucks to electrified trucks, the trade-offs cannot be based solely on the carbon footprint. Indeed, other aspects need to be considered such as operational characteristics, available infrastructure, and costs.

Results from the case study and previous research in the literature demonstrate that **battery electric trucks powered with renewable electricity are a strong decarbonising solution**. Until now, since long-haul trucks need high autonomy, long-haul battery electric trucks are not commercially available yet. Indeed, current electrified trucks have a limited autonomy and long recharging time¹⁶. Therefore, they rather serve for regional and inter-city deliveries. Long distances require larger and heavier batteries, leading to diminished performance, efficiencies, and limited payload. From an economical point of view, the loss in cargo capacity because of heavy batteries and the time loss due to recharging, translates into higher costs and thus impacts the decision making of companies. From this point of view, **FCEV offer a considerable advantage for long-haul trucking, thanks to higher energy density of hydrogen**. Indeed, hydrogen trucks are similar to their diesel counterpart in terms of autonomy, refuelling time, and payload. (Amant et al., 2020; Moultak et al., 2017) It is important to note that green hydrogen by electrolysis still requires twice as much energy to be produced compared to green electricity for BEV. This implies that, to produce green hydrogen, a greater capacity to generate renewable electricity is needed, thus larger investments (Ramachandran & Stimming, 2015).

Additionally, according to the Transport & Environment (2020) the total cost of ownership is higher for FCEV than BEV because of high renewable fuel cost for green hydrogen. The cost parity with diesel is highly variable, it will depend on which cost are assumed, their projections

¹⁶ Volvo announced the launch of electric trucks for regional and intercity deliveries, with operating range up to 300km and about 80% of the battery capacity can be charged with mega chargers in less than 90 minutes. (AB Volvo, 2021)

for the future and the integration of potential subsidies or taxes. Transport & Environment (2020) predict that, for long-haul tractor-trailer trucks, FCEV reach cost parity with diesel by mid-2040s and BEV by early 2030s¹⁷. The report points out that blue hydrogen would offer significantly lower fuel cost, bringing forward cost parity with diesel. So, in the medium- to long-term, after the roll-out of supportive infrastructure, technology advancements in electric powertrains, and some higher taxes on local pollutant and GHG emissions, BEV and FCEV will become more cost competitive than conventional diesel trucks (IEA, 2020a).

Further, the number of electrified trucks entering the fleet will slowly grow and it requires considerable investment in supporting infrastructure such as installations of fast chargers and hydrogen refuelling stations (IEA & OECD, 2017). Here BEV have a slight advantage as electricity is already a commonly used energy carrier. Building recharging stations along with the existing power grid will be available more quickly than building the hydrogen production, distribution, and refuelling infrastructure of which few is already existent (Offer et al., 2010).

Lastly, although the climate benefits of clean energy technologies stay evident, production of batteries give rise to other issues. Indeed, the extraction and exploitation of certain mineral resources (i.e., lithium, cobalt, etc.) can pose socio-environmental issues. Although, minerals have the potential to be recovered and recycled, the recycling channel of batteries is still at early stage. (Amant et al., 2020) Supply chain due diligence, with support of strong regulations, play a key role to increase transparency and traceability in order to identify, evaluate and mitigate risks (IEA, 2021).

Table 6 summarizes overall advantages and disadvantages when comparing BEV and FCEV, powered by renewable electricity and green hydrogen respectively, which could influence the decision-making of companies.

¹⁷ The estimated cost parity with diesel is based on a comparison “excluding any potential subsidies or policies incentives for the FCEV or BEV except for what is already provided for today in France” (Transport & Environment, 2020) and could thus be brought forward.

Table 6: Advantages and disadvantages of renewable electricity and green hydrogen as energy carriers

Energy carrier	Advantages	Disadvantages
Renewable electricity	<ul style="list-style-type: none"> • Zero well-to-wheels GHG emissions • Reduction of local air pollution • High energy efficiency • Lower cost of ownership • Faster roll-out of supportive infrastructure 	<ul style="list-style-type: none"> • Limited autonomy and long recharging time • Payload loss • Extraction of mineral resources for batteries posing socio-environmental issues • Undeveloped recycling channel for batteries
Green hydrogen	<ul style="list-style-type: none"> • Low well-to-wheels GHG emissions • Reduction of local air pollution • High autonomy and fast refuelling time (similar to diesel) • No payload restriction 	<ul style="list-style-type: none"> • Low energy efficiency with current technologies • Higher cost of ownership with fairly high cost of green hydrogen • Slower roll-out of supportive infrastructure

5.3. Limits and further research

An exhaustive conclusion for this section cannot be drawn since a comprehensive analysis of all the possible scenarios is out of the scope of this work. Further research could investigate on the practical implementation of both technologies and the related limitations.

Future work could also take on a broader approach on the sustainability of the energy carriers. The Well-to-Wheels perspective only provides a limited sustainability assessment of the life cycle of heavy-duty trucks, and it does not consider, for instance, the impact of battery production and waste. Moreover, a more systemic approach would allow to encompass other strengths and weaknesses of each technological solution such as resources depletion, competition of uses, infrastructure issues, acceptance, and costs.

6. Conclusion

A comparative study on the environmental performance of conventional diesel trucks, battery electric trucks, and hydrogen fuel cell electric trucks has been conducted. The environmental performance, in terms of energy efficiency and greenhouse gas emissions, is evaluated through a Well-to-Wheels analysis, considering different possible production pathways of diesel, electricity, and hydrogen. The case study is based on a typical use case, considering a semi-trailer tractor with 40 tons gross vehicle mass and 14.29 tons in weighted payload, designed for use in long-haul mission, relatively similar to the use case identified for Colruyt Group as retailer.

Battery electric trucks provide solutions that are less emissive than conventional diesel trucks. They produce no tailpipe emissions, contributing to the reduction of local greenhouse gas emissions and better air quality. However, the Well-to-Wheels greenhouse gas emissions vary largely on the electricity production pathway. The environmental performance of battery electric trucks running on electricity from the grid, depends on the share of fossil fuels in the electricity production mix. When battery electric trucks are powered by the average EU electricity mix in 2016, greenhouse gas emissions are reduced by 35% compared to conventional diesel trucks and will be further reduced to 60% in 2030. In Belgium, the current electricity mix is less carbon intensive, thus presenting stronger greenhouse gas emission reductions up to two third. In 2030, the Belgian nuclear energy is set to be phased out and replaced by renewable energies, natural gas, and a higher share of imported electricity from neighbours. As a result, the carbon footprint of battery electric trucks will increase slightly but remains 60% lower than conventional diesel trucks. Of all the production pathways considered, battery electric trucks powered by renewable energies present the best performance in terms of energy efficiency and they produce zero greenhouse gas emissions, from a well-to-wheels perspective. So, battery electric semi-trailer tractors provide a great potential for tackling climate change but are currently still restricted by other aspects like limited autonomy, long recharging time, lack of infrastructure and socio-environmental issues arising from battery production.

Hydrogen fuel cell electric trucks offer a considerable advantage for long-haul missions, thanks to the higher energy storage density of hydrogen (under pressure) compared to batteries. It allows for high autonomy combined with shorter refuelling time, similar to

conventional diesel trucks. The carbon footprint of **hydrogen fuel cell electric trucks** varies widely depending on the primary energy source. They produce no tailpipe emissions, but only provide a better Well-to-Wheels environmental performance than diesel trucks, for specific production pathways. Indeed, hydrogen to power the truck should either be “green”, produced by electrolysis with electricity from renewable energy sources, or “blue”, produced by steam methane reforming combined with carbon capture and storage. “Grey” hydrogen, produced by steam methane reforming without carbon capture, is considered less relevant to significantly reduce the carbon footprint of trucks. Whereas hydrogen produced by electrolysis with the current and future electricity mixes in Europe and Belgium, results in a worse environmental performance than its diesel counterpart and thus needs to be excluded.

Green hydrogen to power trucks decreases greenhouse gas emissions by more than 90% compared to diesel but remains slightly more emissive than battery electric trucks powered by renewable electricity. Also, fuel cell electric trucks powered by hydrogen from electrolysis require about double the energy compared to battery electric trucks, because of low conversion efficiencies from electricity-to-hydrogen-to-electricity. So, due to energy losses, current electrolysis and fuel cell technologies do not offer the best solution yet to include renewable sources of electricity, as these could be used more efficiently through battery electric trucks. If renewable energy sources are not available or not sufficient to produce green hydrogen, blue hydrogen also provides a potential alternative. Despite an energy penalty for carbon capture, blue hydrogen powered trucks reduce Well-to-Wheels greenhouse gas emissions by two third, relative to conventional diesel trucks.

To conclude, battery electric trucks powered by renewable electricity provide the best environmental performance, with zero greenhouse gas emissions and low primary energy sources consumption. Nevertheless, limited autonomy and long recharging time are currently preventing this solution to be suitable for long-haul missions and would be more suitable for regional and urban deliveries. Hydrogen fuel cell trucks thus offer a potential alternative, by overcoming this challenge, and can play a key role in the decarbonisation of long-haul semi-trailer tractors. In this case, green hydrogen is the favourite solution in terms of environmental performance, but it requires significant investments to build renewable energy capacities. Technology advancements are expected to improve the energy conversion efficiencies, making this solution more attractive in the future. In the meantime, blue

hydrogen, despite being produced from a fossil gas, can also be considered as a viable alternative to reduce the carbon footprint of semi-trailer tractors.

7. Bibliography

- AB Volvo. (2021). *Volvo Trucks dévoile la technologie de ses nouveaux poids lourds électriques*.
<https://www.volvotrucks.be/fr-be/news/press-releases/2021/jun/technology-in-new-heavy-duty-electric-trucks.html>
- Amant, S., Meunier, N., & de Cossé Brissac, C. (2020). *Road transportation: What alternative motorisations are suitable for the climate*. Carbone 4. <http://www.carbone4.com/wp-content/uploads/2021/02/Road-transportation-what-alternative-motorisations-are-suitable-for-the-climate-Carbone-4.pdf>
- Calvo Ambel, C., Earl, T., Samuel, K., Cornelis, S., & Sihvonen, J. (2017). *Roadmap to climate-friendly land freight and buses in Europe*. Transport and Environment.
<https://www.transportenvironment.org/publications/roadmap-climate-friendly-land-freight-and-buses-europe>
- Campanari, S., Manzolini, G., & Garcia de la Iglesia, F. (2009). Energy analysis of electric vehicles using batteries or fuel cells through well-to-wheel driving cycle simulations. *Journal of Power Sources*, 186(2), 464–477. <https://doi.org/10.1016/j.jpowsour.2008.09.115>
- CertifHy. (2021). *An Emerging Green and Low Carbon Hydrogen Market in Europe*.
<https://www.certifhy.eu/9-uncategorised/174-an-emerging-green-and-low-carbon-hydrogen-market-in-europe.html>
- Chevron Corporation. (2007). *Diesel Fuels Technical Review*.
<https://www.onsitepoweradvisor.com/wp-content/uploads/2011/12/Chevron-DFTR.pdf>
- Climate Policy Info Hub. (n.d.). *Glossary*. Climate Policy Info Hub. Retrieved 10 June 2021, from <https://climatepolicyinfohub.eu/glossary/4.html>
- Compiègne, V., & Peythieu, A. (2020). *Hydrogen power Enabling a virtuous decarbonisation loop*. Candriam.
file:///C:/Users/manon/OneDrive/Documents/UCL/M%C3%A9moire/M%C3%A9moire%20recherche_hydrogen/2020_10_hydrogen_en_web.pdf

- Daimler Truck AG. (2021). *E-FUSO Vision One | Daimler Truck AG*. Daimler Truck AG.
<https://www.daimler-truck.com/innovation-sustainability/efficient-emission-free/efuso-vision-one.html>
- Delgado, O., Miller, J., Sharpe, B., & Muncrief, R. (2016). *Estimating the fuel efficiency technology potential of heavy-duty trucks in major markets around the world*. Global Fuel Economy Initiative. <http://www.globalfueleconomy.org/media/404893/gfei-wp14.pdf>
- Delucchi, M. A., & Lipman, T. E. (2010). Chapter Two—Lifetime Cost of Battery, Fuel-Cell, and Plug-in Hybrid Electric Vehicles. In G. Pistoia (Ed.), *Electric and Hybrid Vehicles* (pp. 19–60). Elsevier.
<https://doi.org/10.1016/B978-0-444-53565-8.00002-6>
- Earl, T., Mathieu, L., Cornelis, S., Kenny, S., Calvo Ambel, C., & Nix, J. (2018). *Analysis of long-haul battery electric trucks in EU*.
https://www.transportenvironment.org/sites/te/files/publications/20180725_T&E_Battery_Electric_Trucks_EU_FINAL.pdf
- Edwards, R., Larivé, J.-F., Rickeard, D. J., Lonza, L., Hass, H., & Maas, H. (2014). *Well-to-wheels report version 4.a: JEC well to wheels analysis: well to wheels analysis of future automotive fuels and powertrains in the European context*. (Vol. 113). Publications Office of the European Union. <https://data.europa.eu/doi/10.2790/95533>
- EEA. (2018, December 18). *Overview of electricity production and use in Europe—European Environment Agency* [Indicator Assessment]. European Environment Agency.
<https://www.eea.europa.eu/data-and-maps/indicators/overview-of-the-electricity-production-2/assessment-4>
- EEA. (2020). *Greenhouse gas emissions by aggregated sector* [Data Visualization]. European Environment Agency. <https://www.eea.europa.eu/data-and-maps/daviz/ghg-emissions-by-aggregated-sector-5#tab-dashboard-02>
- E-Force. (2021). *E-Force One AG - EF26 KSF*. <https://www.eforce.ch/en/products/ef26-ksf>

- Elia Group. (2017). *Electricity scenarios for Belgium towards 2050—Elia’s quantified study on the energy transition in 2030 and 2040* [Study].
- Elia Group. (2021, January 7). *Belgium’s electricity mix in 2020: Renewable generation up 31% in a year marked by the COVID-19 crisis*. https://www.elia.be/en/news/press-releases/2021/01/20210107_belgium-s-electricity-mix-in-2020
- ETC. (2018). *Mission Possible: Reaching net-zero carbon emissions from harder to dabate sectors by mid-century* (p. 172). Energy Transitions Commission. <https://www.energy-transitions.org/publications/mission-possible/>
- European Commission. (2016, November 14). *Well-to-Wheels Analyses* [Text]. EU Science Hub - European Commission. <https://ec.europa.eu/jrc/en/jec/activities/wtw>
- European Commission. (2018). *In-depth analysis in support of the Commission Communication COM (2018)773: A Clean Planet for all—A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy*. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52018DC0773>
- European Commission. (2019). *REGULATION (EU) 2019/1242 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL* (O. Radley-Gardner, H. Beale, & R. Zimmermann, Eds.). Hart Publishing. <https://doi.org/10.5040/9781782258674>
- European Commission. (2021). *Corporate sustainability reporting* [Text]. European Commission. https://ec.europa.eu/info/business-economy-euro/company-reporting-and-auditing/company-reporting/corporate-sustainability-reporting_en
- European Union. (2021). *Climate action in Belgium*.
- Eurostat. (2018, May 31). *Eurostat: Supply, transformation and consumption of solid fuels—Annual data [nrg_101a]*. Eurostat. <https://ec.europa.eu/eurostat/web/energy/data/database>
- Fluxys Belgium & Fluxys LNG. (2021). *Indicative investment plan 2021-2030*. <https://www.fluxys.com/>

/media/project/fluxys/public/corporate/fluxyscom/documents/fluxys-belgium/corporate/tyndp/2021/tyndp_flx_be_lng_2021_2030_en_external.pdf

FPS Economy. (n.d.). *International gas trade in Belgium: Determining the origin and destination of imports and exports, and eliminating transit from annual data*. Séverine Waterbley.

Retrieved 26 June 2021, from <https://www.fluxys.com/>-

/media/project/fluxys/public/corporate/fluxyscom/documents/fluxys-belgium/corporate/tyndp/2021/tyndp_flx_be_lng_2021_2030_en_external.pdf

GHG Protocol. (2011). *GHG Protocol Corporate Value Chain (Scope 3) Accounting and Reporting Standard* (GHG Protocol Corporate Accounting and Reporting Standard). World Resources Institute and World Business Council for Sustainable Development.

<https://ghgprotocol.org/standards/scope-3-standard>

Gustafsson, M., Svensson, N., Eklund, M., Dahl Öberg, J., & Vehabovic, A. (2021). Well-to-wheel greenhouse gas emissions of heavy-duty transports: Influence of electricity carbon intensity. *Transportation Research Part D: Transport and Environment*, 93, 102757.

<https://doi.org/10.1016/j.trd.2021.102757>

Hirsch, J. (2019, November 12). *Hyundai, Nikola and Toyota Start to Build Hydrogen Highway*.

Trucks.Com. <https://www.trucks.com/2019/11/12/hyundai-nikola-toyota-build-hydrogen-highway/>

Hydrogen Mobility Europe. (2015, November 19). *FCEVs*. Hydrogen Mobility Europe.

<https://h2me.eu/about/fcevs/>

Hydrogen Tools. (n.d.). *Lower and Higher Heating Values of Fuels*. Hydrogen Tools. Retrieved 10 August 2021, from <https://h2tools.org/hyarc/calculator-tools/lower-and-higher-heating-values-fuels>

ICCT. (n.d.). *Heavy-duty vehicle efficiency*. International Council on Clean Transportation. Retrieved 10 August 2021, from <https://theicct.org/heavy-duty-vehicle-efficiency>

- IEA. (2020a). *Energy Technology Perspectives 2020*. International Energy Agency.
https://iea.blob.core.windows.net/assets/7f8aed40-89af-4348-be19-c8a67df0b9ea/Energy_Technology_Perspectives_2020_PDF.pdf
- IEA. (2020b). *European Union 2020*. International Energy Agency.
<https://www.iea.org/reports/european-union-2020>
- IEA. (2021). *The Role of Critical Minerals in Clean Energy Transitions* (World Energy Outlook). International Energy Agency. <https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions>
- IEA & OECD. (2017). *The Future of Trucks—Implications for energy and the environment* (No. 2). International Energy Agency. <https://www.iea.org/reports/the-future-of-trucks>
- IPCC. (2018). *Global Warming of 1.5 °C*. Intergovernmental Panel on Climate Change.
<https://www.ipcc.ch/sr15/>
- ISO 13600. (1997). *Technical energy systems—Basic concepts*. ISO.
<https://www.iso.org/obp/ui/#iso:std:iso:13600:ed-1:v1:en>
- Langston, L. S. (2014). Turbines, Gas. In *Reference Module in Earth Systems and Environmental Sciences*. Elsevier. <https://doi.org/10.1016/B978-0-12-409548-9.09044-8>
- Lee, D.-Y., Elgowainy, A., Kotz, A., Vijayagopal, R., & Marcinkoski, J. (2018). Life-cycle implications of hydrogen fuel cell electric vehicle technology for medium- and heavy-duty trucks. *Journal of Power Sources*, 393, 217–229. <https://doi.org/10.1016/j.jpowsour.2018.05.012>
- Lohse-Busch, H., Stutenberg, K., Duoba, M., Liu, X., Elgowainy, A., Wang, M., Wallner, T., Richard, B., & Christenson, M. (2020). Automotive fuel cell stack and system efficiency and fuel consumption based on vehicle testing on a chassis dynamometer at minus 18 °C to positive 35 °C temperatures. *International Journal of Hydrogen Energy*, 45(1), 861–872.
<https://doi.org/10.1016/j.ijhydene.2019.10.150>

- Lombardi, S., Tribioli, L., Guandalini, G., & Iora, P. (2020). Energy performance and well-to-wheel analysis of different powertrain solutions for freight transportation. *International Journal of Hydrogen Energy*, 45(22), 12535–12554. <https://doi.org/10.1016/j.ijhydene.2020.02.181>
- Malins, C., Galarza, S., Baral, A., & Kodjak, D. (2014). *Upstream Emissions of Fossil Fuel Feedstocks for Transport Fuels Consumed in the European Union* (pp. 1–510). International Council on Clean Transportation.
- Mansour, C. J., & Haddad, M. G. (2017). Well-to-wheel assessment for informing transition strategies to low-carbon fuel-vehicles in developing countries dependent on fuel imports: A case-study of road transport in Lebanon. *Energy Policy*, 107, 167–181. <https://doi.org/10.1016/j.enpol.2017.04.031>
- Merriam-Webster. (n.d.). *Definition of BASELOAD*. Merriam-Webster.Com Dictionary. Retrieved 10 June 2021, from <https://www.merriam-webster.com/dictionary/baseload>
- Moro, A., & Lonza, L. (2018). Electricity carbon intensity in European Member States: Impacts on GHG emissions of electric vehicles. *Transportation Research Part D: Transport and Environment*, 64, 5–14. <https://doi.org/10.1016/j.trd.2017.07.012>
- Moultak, M., Lutsey, N., & Hall, D. (2017). *Transitioning to zero-emission heavy-duty freight vehicles*. International Council on Clean Transportation.
- National Centre for Environmental Health. (2021, July 20). *Air Pollutants | Air | CDC*. Centers for Disease Control and Prevention. <https://www.cdc.gov/air/pollutants.htm>
- OECD. (n.d.). *Air and climate—Air and GHG emissions—OECD Data*. Organisation for Economic Co-Operation and Development. Retrieved 10 June 2021, from <https://data.oecd.org/air/air-and-ghg-emissions.htm>
- Offer, G. J., Howey, D., Contestabile, M., Clague, R., & Brandon, N. P. (2010). Comparative analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system. *Energy Policy*, 38(1), 24–29. <https://doi.org/10.1016/j.enpol.2009.08.040>

Office of Energy Efficiency & Renewable Energy. (n.d.-a). *Hydrogen Production: Electrolysis*.

Energy.Gov. Retrieved 26 June 2021, from

<https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis>

Office of Energy Efficiency & Renewable Energy. (n.d.-b). *Hydrogen Production: Natural Gas*

Reforming. Energy.Gov. Retrieved 11 August 2021, from

<https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming>

Prussi, M., Yugo, M., De Prada, L., Padella, M., & Edwards, R. (2020). *JEC Well-to-Wheels report V5:*

JEC well to wheels analysis : well to wheels analysis of future automotive fuels and powertrains in the European context. Publications Office of the European Union.

<https://data.europa.eu/doi/10.2760/100379>

Prussi, M., Yugo, M., De Prada, L., Padella, M., Edwards, R., & Lonza, L. (2020a). *JEC Well-to-Tank*

report v5: Annexes: JEC well to wheels analysis : well to wheels analysis of future automotive fuels and powertrains in the European context. Publications Office of the European Union.

<https://data.europa.eu/doi/10.2760/06704>

Prussi, M., Yugo, M., De Prada, L., Padella, M., Edwards, R., & Lonza, L. (2020b). *JEC Well-to-Tank*

report V5: JEC well to wheels analysis : well to wheels analysis of future automotive fuels and powertrains in the European context. Publications Office of the European Union.

<https://data.europa.eu/doi/10.2760/959137>

Ramachandran, S., & Stimming, U. (2015). Well to wheel analysis of low carbon alternatives for road traffic. *Energy & Environmental Science*, 8(11), 3313–3324.

<https://doi.org/10.1039/C5EE01512J>

Rangaraju, S., De Vroey, L., Messagie, M., Mertens, J., & Van Mierlo, J. (2015). Impacts of electricity mix, charging profile, and driving behavior on the emissions performance of battery electric vehicles: A Belgian case study. *Applied Energy*, 148, 496–505.

<https://doi.org/10.1016/j.apenergy.2015.01.121>

- Röck, M., Martin, R., & Hausberger, S. (2020). *JEC Tank-To-Wheels report v5: Heavy duty vehicles* (M. Prussi, M. Yugo, L. Lonza, L. De Prada, P. Hanarp, C. Bersia, M. Colombano, H. Gräser, G. Gomes Marques, H. Mikaelsson, & H. Hamje, Eds.). Publications Office of the European Union. <https://data.europa.eu/doi/10.2760/959137>
- Rousseau, A., & Sharer, P. (2004). Comparing Apples to Apples: Well-to-Wheel Analysis of Current ICE and Fuel Cell Vehicle Technologies. *SAE Transactions*, *113*, 610–619. JSTOR.
- Sacchi, R., Bauer, C., & Cox, B. L. (2021). Does Size Matter? The Influence of Size, Load Factor, Range Autonomy, and Application Type on the Life Cycle Assessment of Current and Future Medium- and Heavy-Duty Vehicles. *Environmental Science & Technology*, *55*(8), 5224–5235. <https://doi.org/10.1021/acs.est.0c07773>
- Schlapbach, L. (2011). Hydrogen as a Fuel and Its Storage for Mobility and Transport. *MRS Bulletin*, *27*(9), 675–679. <https://doi.org/10.1557/mrs2002.220>
- Sen, B., Ercan, T., & Tatari, O. (2017). Does a battery-electric truck make a difference? – Life cycle emissions, costs, and externality analysis of alternative fuel-powered Class 8 heavy-duty trucks in the United States. *Journal of Cleaner Production*, *141*, 110–121. <https://doi.org/10.1016/j.jclepro.2016.09.046>
- Smallbone, A., Jia, B., Atkins, P., & Roskilly, A. P. (2020). The impact of disruptive powertrain technologies on energy consumption and carbon dioxide emissions from heavy-duty vehicles. *Energy Conversion and Management: X*, *6*, 100030. <https://doi.org/10.1016/j.ecmx.2020.100030>
- Solar Impulse. (2021). *Hydrogen mobility: Solutions for the future of mobility*. Solar Impulse Foundation. <https://solarimpulse.com/hydrogen-mobility-solutions>
- Sorrell, S. (2015). Reducing energy demand: A review of issues, challenges and approaches. *Renewable and Sustainable Energy Reviews*, *47*, 74–82. <https://doi.org/10.1016/j.rser.2015.03.002>

Statista. (2020, November 6). *Uranium imports to the EU by country of origin 2019*. Statista.

<https://www.statista.com/statistics/1147442/imports-of-uranium-to-eu-by-country/>

The London School of Economics and Political Science. (2018, May 1). *What is carbon capture and storage and what role can it play in tackling climate change?* Grantham Research Institute on Climate Change and the Environment.

<https://www.lse.ac.uk/granthaminstitute/explainers/what-is-carbon-capture-and-storage-and-what-role-can-it-play-in-tackling-climate-change/>

Torchio, M. F., & Santarelli, M. G. (2010). Energy, environmental and economic comparison of different powertrain/fuel options using well-to-wheels assessment, energy and external costs – European market analysis. *Energy*, 35(10), 4156–4171.

<https://doi.org/10.1016/j.energy.2010.06.037>

Towler, B. F. (2014). Nuclear Energy. In B. F. Towler (Ed.), *The Future of Energy* (pp. 135–159).

Academic Press. <https://doi.org/10.1016/B978-0-12-801027-3.00007-5>

Transport & Environment. (2020). *Comparison of hydrogen and battery electric trucks. Methodology and underlying assumptions*. Transport and Environment.

https://www.transportenvironment.org/sites/te/files/publications/2020_06_TE_comparison_hydrogen_battery_electric_trucks_methodology.pdf

University of Calgary. (n.d.). *Energy density—Energy Education*. Retrieved 10 June 2021, from

https://energyeducation.ca/encyclopedia/Energy_density

van der Zwaan, B., Keppo, I., & Johnsson, F. (2013). How to decarbonize the transport sector? *Energy Policy*, 61, 562–573. <https://doi.org/10.1016/j.enpol.2013.05.118>

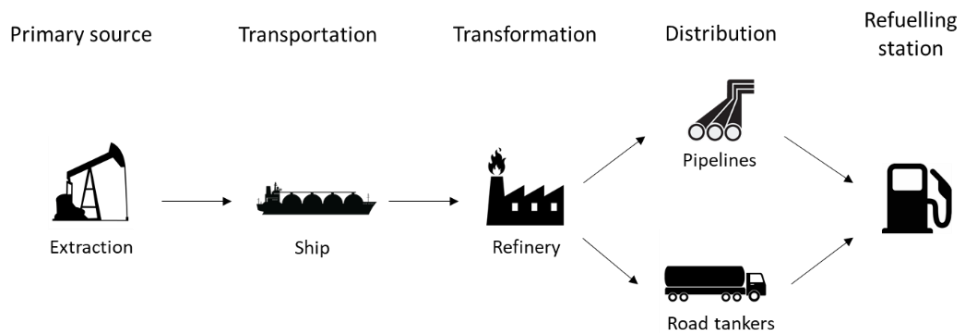
WHO. (2021). *How air pollution is destroying our health*. World Health Organization.

<https://www.who.int/news-room/spotlight/how-air-pollution-is-destroying-our-health>

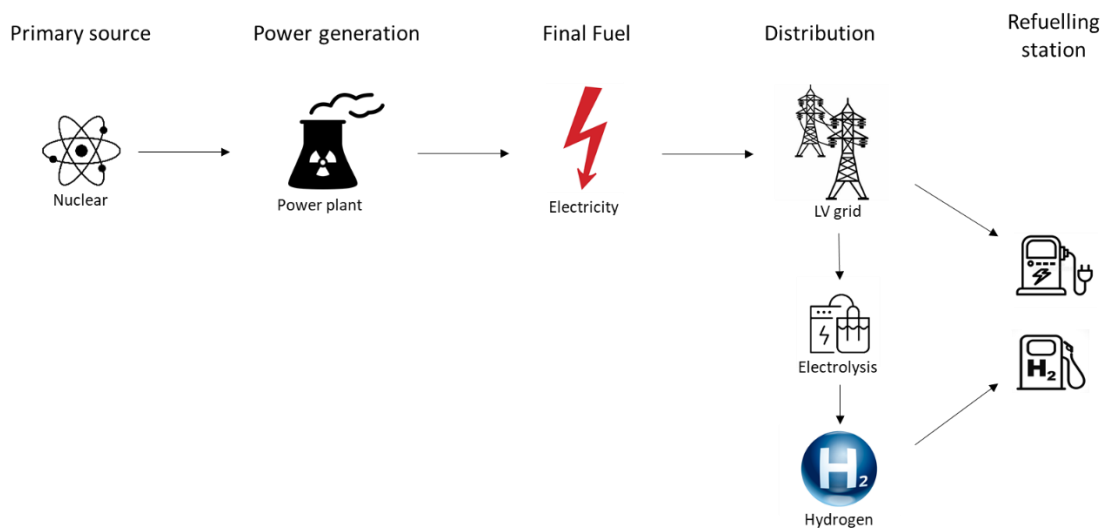
8. Appendices

Appendix A: Investigated production pathways for diesel, electricity, and hydrogen

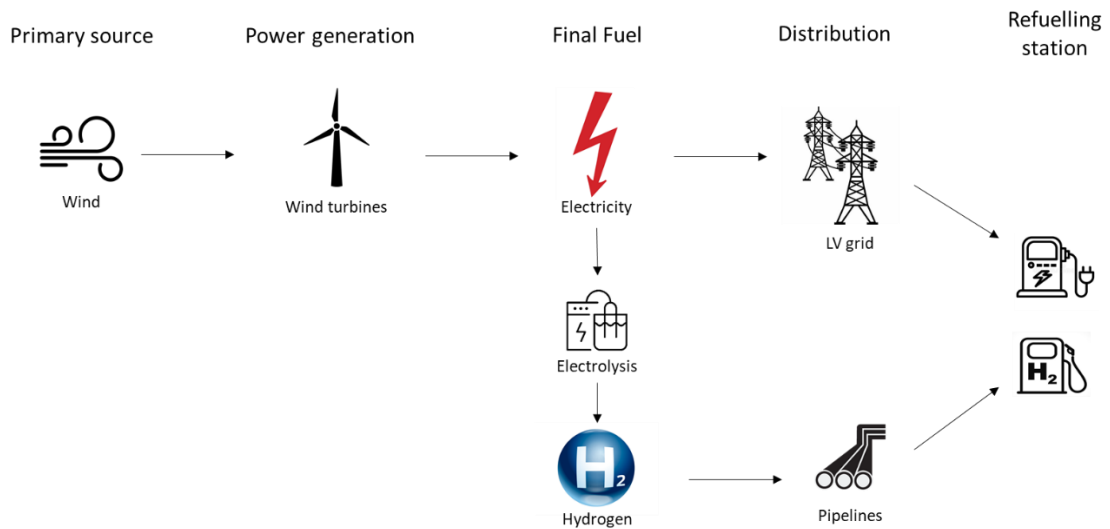
- a. **(ICEV) Diesel:** Crude oil from typical EU supply → transport by sea → refining in EU
(marginal **diesel** production) → typical EU distribution and retail



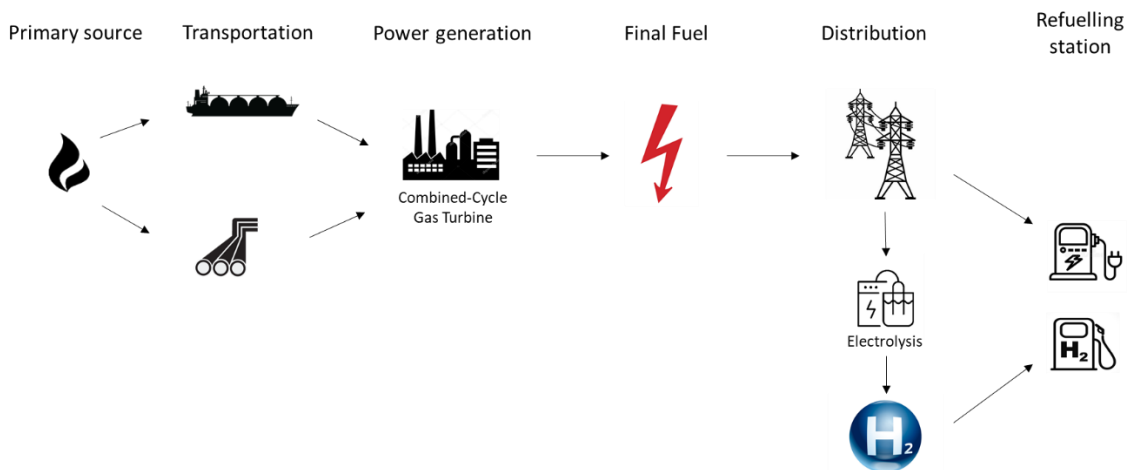
- b. **(BEV) Nuclear:** Nuclear fuel (uranium) provision → nuclear power plant (**electricity** generation) → Low Voltage grid
- c. **(FCEV) Nuclear:** Nuclear fuel (uranium) provision → nuclear power plant (electricity generation) → on-site electrolyser (**hydrogen** production) + compression



- d. **(BEV) Wind:** Wind → Wind turbines (on/offshore) (**electricity** generation) → Low Voltage grid
- e. **(FCEV) Wind:** Wind → Wind turbines (offshore) (electricity generation) + central electrolyser ("**green**" **hydrogen** production) → distribution by pipeline (50km) + compression

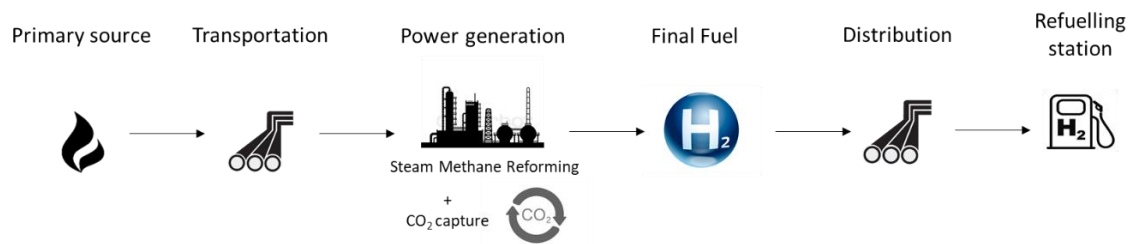


- f. **(BEV) LNG:** Remote NG → liquefaction → shipping LNG → CCGT (electricity generation) → Low Voltage grid
- g. **(FCEV) LNG:** Remote NG → liquefaction → shipping LNG → CCGT (electricity generation) → on-site electrolyser (hydrogen production) + compression
- h. **(BEV) piped NG:** Piped NG → pipeline into Europe (4000km) → CCGT (electricity generation) → Low Voltage grid
- i. **(FCEV) piped NG:** Piped NG → pipeline into Europe (4000km) → CCGT (electricity generation) → on-site electrolyser (hydrogen production) + compression

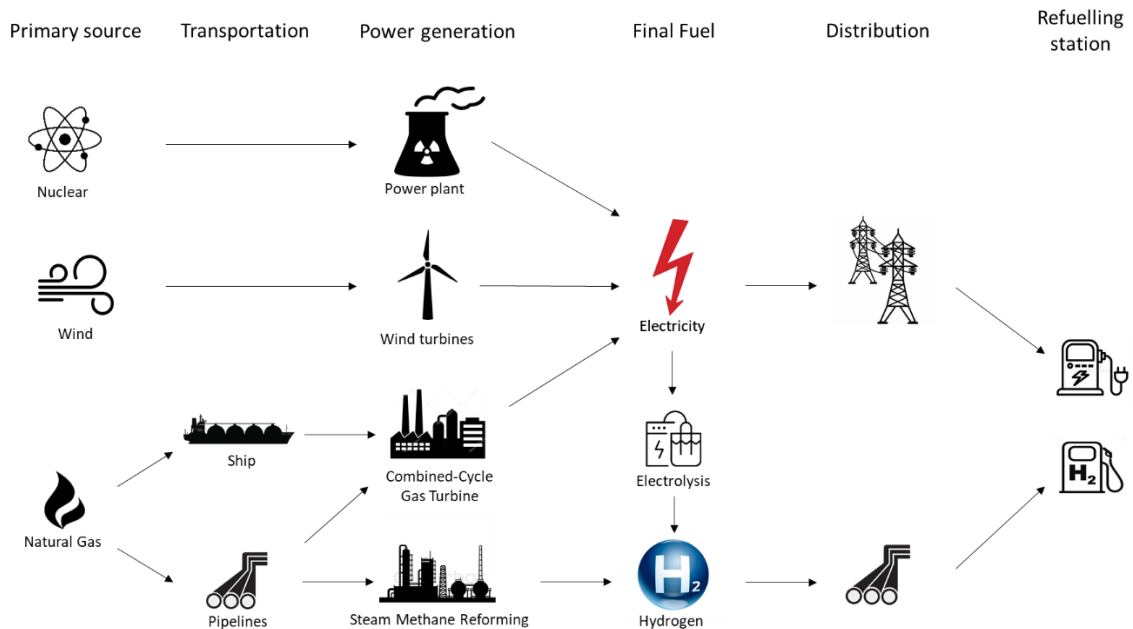


- j. Piped NG → pipeline into Europe (4000km) → Steam Methane Reforming (hydrogen production) → pipeline (50km) + compression
- ("grey")

- k. Piped NG → pipeline into Europe (4000km) → Steam Methane Reforming + Carbon Capture (“blue” hydrogen production) → pipeline (50km) + compression



- l. EU primary resource mix → EU electricity mix 2016 → Medium Voltage grid
- m. EU primary resource mix → EU electricity mix 2030 → Medium Voltage grid
- n. EU primary resource mix → EU electricity mix 2016 → Medium Voltage grid → on-site electrolyser (hydrogen production) + compression
- o. EU primary resource mix → EU electricity mix 2030 → Medium Voltage grid → on-site electrolyser (hydrogen production) + compression
- p. EU primary resource mix → EU electricity mix 2016 → High Voltage grid + central electrolyser (hydrogen production) → pipelines (50km) + compression
- q. EU primary resource mix → EU electricity mix 2030 → High Voltage grid + central electrolyser (hydrogen production) → pipelines (50km) + compression



Abstract

In 2019, the heavy-duty vehicles in Europe were responsible for about a quarter of road transport CO₂ emissions and represented 6% of total European CO₂ emissions. Heavy-duty vehicles play a critical role in the supply chain of organisations, by delivering all types of goods from the production points to the manufacturing sites and to their final selling point. To reduce the environmental impact of supply chains, all emission reduction levers need to be activated. An impactful reduction lever is the use of alternative fuels and powertrains for heavy-duty vehicles. Battery electric trucks and hydrogen fuel cell electric trucks are the most promising alternatives until now. Therefore, this paper evaluates the environmental performance, in terms of “energy efficiency” and “greenhouse gas emissions”, for battery electric trucks and hydrogen fuel cell electric trucks. Both are being compared to conventional diesel trucks, to assess their potential to deeply reduce emissions. The study investigates several production pathways for each fuel. The environmental performance is based on a Well-to-Wheels analysis.

UNIVERSITÉ CATHOLIQUE DE LOUVAIN
Louvain School of Management

Place des Doyens, 1 bte L2.01.01, 1348 Louvain-la-Neuve
Boulevard Emile Devreux 6, 6000 Charleroi, Belgique
Chaussée de Binche 151, 7000 Mons, Belgique

www.uclouvain.be/lsm