MSc Program
Renewable Energy Systems

ACADEMY FOR CONTINUING EDUCATION

Potentials and limitations of green hydrogen as an energy carrier for decarbonising the transport sector in Austria

A Master's Thesis submitted for the degree of
“Master of Science”

supervised by
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Vienna, 23.02.2022

Affidavit

I, **MAG. HANNES LOACKER, CFA**, hereby declare

1. that I am the sole author of the present Master's Thesis, "POTENTIALS AND LIMITATIONS OF GREEN HYDROGEN AS AN ENERGY CARRIER FOR DECARBONISING THE TRANSPORT SECTOR IN AUSTRIA", 116 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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Signature

"Water will be the coal of the future"

(Jules Verne, The Mysterious Island, 1874)

Abstract

Do fuel cell electric vehicles have a future? This is one of the most controversial questions when it comes to future mobility. Looking at the current fleet of fuel cell electric cars at just over 40,000 vehicles worldwide, many an automaker has also begun to tune in to the fuel cell's swan song. The aim of this master thesis is to show in which areas the fuel cell has potential, but also where its limits lie. With the help of the GREET® model, the carbon dioxide saving potentials compared to internal combustion engine vehicles are calculated along the entire vehicle operation pathway (well-to-wheel). Furthermore, the focus is on the economic efficiency of green hydrogen and of fuel cell electric vehicles themselves. The latter is to be presented on the basis of the total cost of ownership approach in a comparison with internal combustion engines and battery electric vehicles. The results of such a comparison show that the competitiveness of a fuel cell electric vehicle increases the larger the vehicle or the higher the annual mileage. For smaller vehicles and lower annual mileage, a battery electric vehicle has a clear competitive edge over fuel cell electric cars. With regard to the avoidance of carbon dioxide emissions, the results of this master thesis show that the contribution of fuel cell electric vehicles in the Austrian transport sector remains very manageable in a "base scenario" with less than 2% of avoided carbon dioxide emissions in 2050. In a “decarbonisation scenario” with strong growth rates of fuel cell electric vehicles in the commercial vehicle segments, the picture is completely different. Here, up to almost a quarter of the current transport-related carbon dioxide emissions could be saved in 2050, but as a result electricity demand could also increase by almost 35% compared to today, thus necessitating an even greater expansion of renewable energy capacities.

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Introduction

Hydrogen (H_2) has had several false starts in recent decades. At the same time, hydrogen has in the past repeatedly been associated with the hope that this technology can make an important contribution to decarbonisation over the past decades. (Staffell et al. 2019: 1) What is the case against another false start? And if there is one, what contribution can green hydrogen make to the decarbonisation of Austrian transport? Where are the biggest hurdles on the path ahead?

In order to answer these questions, it is advisable to first look one level deeper and clarify why technological progress is needed for decarbonisation and why there is justified hope that clean technologies such as green hydrogen can play an important role here.

Climate change is a reality. Global warming has increased significantly in recent decades. And there is no question that human influences have contributed to global warming. (IPCC 2021: 6) Worldwide, the average temperature measured between 2011-2020 was 1.09°C higher (bandwidth 0.68 to 1.83°C) than in the period 1850-1900. This period corresponds to the first period with sufficient available measurements and is used as a baseline for the conditions that prevailed at the pre-industrial level. (IPCC 2021: 6)

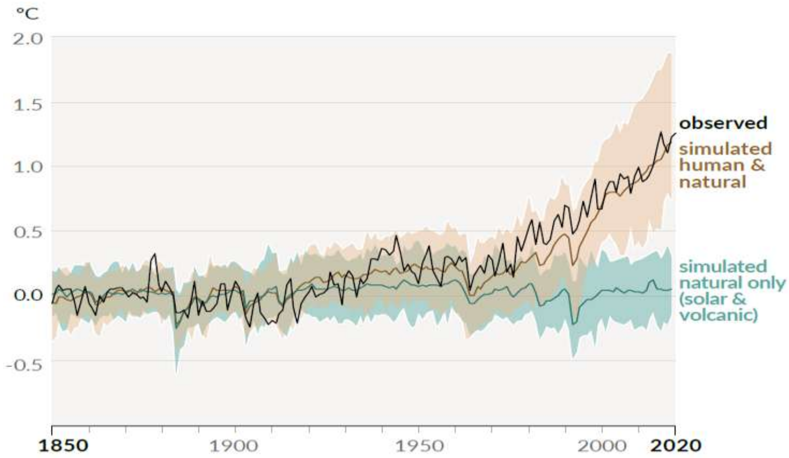

Figure 1: Change in global surface temperature relative to 1850-1900 (IPCC 2021: 8)

In Figure 1, two observation areas were observed and simulated over 170 years each. The first observation period (turquoise area) simulates which natural effects cause a change of the surface temperature. The second observation period (light brown area) simulates the effect of both natural and human-induced changes on the surface temperature. Comparing the mean of the second simulation with the actual observed changes of the surface temperature (black line), it can be seen that the deviations are within 0.2°C over the largest period. And it suggests that the human induced effects are crucial for the temperature increase since the 70s/80s at the latest. In 2020, global warming was already 1.2°C above the baseline on average. The years 2015-2020 were the six warmest since records began. (World Meteorological Organization 2021: 4, 5)

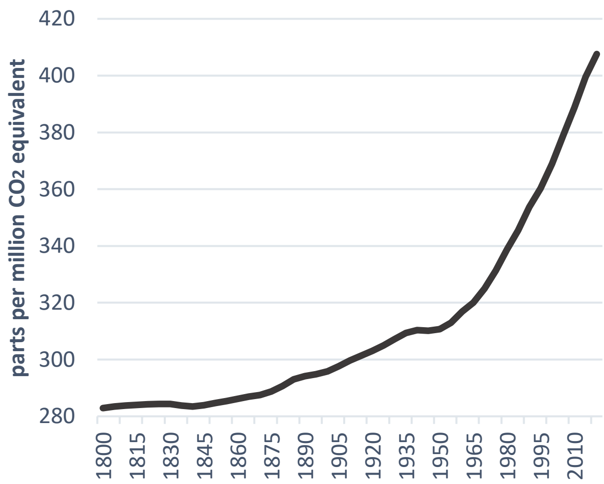

Figure 2: Atmospheric concentration of CO_2 equivalent (European Environment Agency 2019: online)

Figure 2 shows that the atmospheric concentration measured in parts per million (ppm) carbon dioxide equivalent (CO_{2eq}) has increased from less than 300 to more than 400 since industrial revolution. In the IPCC fifth assessment report (AR5), the working group states that there is high confidence that an anthropogenic GHG-induced temperature increase to above 2°C in 2100 is likely to be avoided as long as the atmospheric concentration is around 450 ppm. Up to a value of 500 ppm CO_2eq, it is more likely that this is the case than that it is not. Above 530 ppm CO_2eq, in turn, it is more likely that the temperature increase will be above 2°C than that it will be below. (IPCC 2014: 28) In 2019, the atmospheric concentration was already 410 ppm CO_2eq. Before the industrial revolution, this value had been between 174 ppm and 300 ppm CO_2eq. (IPCC 2021: 6, 210)

The consequences of global warming could, without any doubt, be dramatic in their impact on our habitat. Already a significant overshoot of 1.5°C in the direction of 2.0°C would already be associated with an increase in areas affected by runoffs and flood hazards, among other things. (IPCC 2019: 178) According to studies, things look really sobering at a warming of 2°C to 3°C. Thus, the Arctic would likely be ice-free in summer, resulting in a reduction of habitat for polar bears, seals, whales, and seabirds. At least as bad would be a possible thawing of permafrost soils, as this would release greenhouse gases (GHG), which in turn would accelerate climate change all the more. Besides, an even more pronounced rise in sea level would be inevitable, leading to increased flooding and land loss. Other areas of the world, on the other hand, would experience reduced water resources. And an increase in heat waves would very likely have a negative impact on crop yields. (IPCC 2019: 261) The list could easily be continued but would not change the urgency and necessity of the fight against climate change.

Clearly, this is a global problem, as is also addressed in the Paris Climate Agreement. And it has been triggered, and is still being triggered, above all to a good extent by fossil energy sources. Between 1850 and 2020, they contributed to a good two-thirds of the increase in carbon dioxide (CO_2) concentration in the atmosphere. Coal accounted for 101 ppm, oil for 76 ppm, and natural gas for 34 ppm. Land use (95 ppm) and cement (6 ppm) were responsible for the remaining part. (Global Carbon Project 2021: 57) In specific terms, this means that in order to curb global warming, fossil fuels must be successively eliminated from the global energy mix. Ultimately, this will require enormous efforts on the part of all countries to significantly reduce the greenhouse gases emitted each year and thus curb the rise in global warming. (United Nations 2021: online; Vronisti et al. 2020: 10) This will require a bundle of technologies. Hydrogen is one of them from today's perspective.

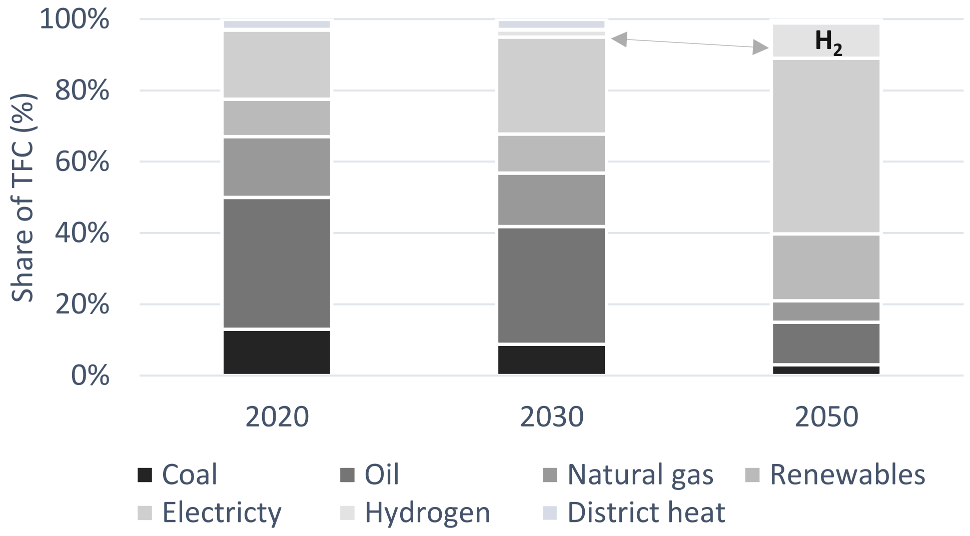

Figure 3: Share of total final energy consumption (TFC) by fuel in the net zero emissions scenario (NZE), 2020-2050 (IEA 2021a: 19)

Figure 3 shows a breakdown of total final energy consumption in the IEA's "net zero emissions scenario" (NZE). In this scenario, the share of hydrogen increases from 1.5% in 2030 to around 10% in 2050. Accordingly, the share of renewables will rise from around 10% in 2020 to around 19% in 2050, and that of electricity from around 20% to just under 50%. By contrast, the share of coal will fall from 13% to 3%, that of gas from 17% to 6% and that of oil from 37% to 12%.

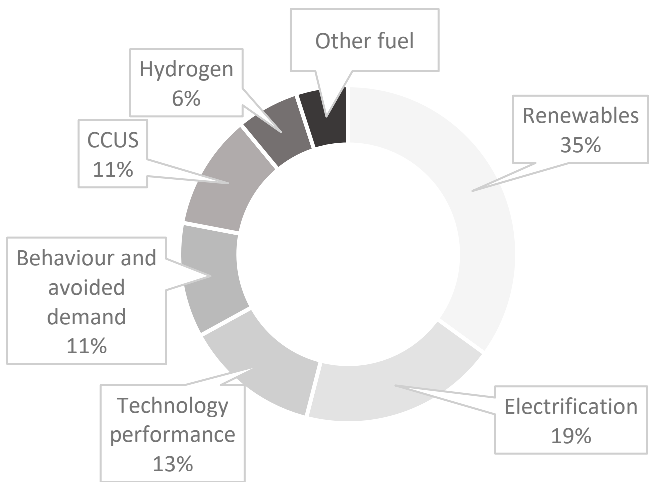

Figure 4: Cumulative emissions by mitigation measure in the NZE, 2020-2050 (IEA 2021a: 19)

Figure 4 shows the percent contribution of each measure to reducing CO_2 emissions in 2050 in the IEA's NZE scenario. The contribution of hydrogen to emissions avoidance is around 6.5%. The largest share is accounted for by renewables with 35%, followed by electrification (19%), technology performance (13%), carbon capture, utilization and storage (CCUS, 11%), behaviour and avoided demand (11%). (IEA 2021a: 19-20)
Also, the energy mix in Austria will continue to change in the coming decades. As a signatory to the Paris Climate Agreement, which was adopted by 195 countries in December, Austria has committed itself to making its contribution to achieving the global climate targets. (Bundesministerium für Nachhaltigkeit und Tourismus 2018: 14) In addition, the Austrian federal government has proclaimed the goal of making Austria climate neutral as early as 2040. (Republic of Austria 2020: 73)
The transport sector plays a key role in this. In 2019, the last year before the Covid-19 pandemic, around 30% of greenhouse gas emissions in Austria were caused by transport. (Umweltbundesamt 2021: 122) Hydrogen can and should play a significant role here in reducing emissions in this sector. The IEA forecasts a growth of the global transport sector from 20 thousand (k) tonnes of hydrogen in 2020 to more than 100 million (mn) tonnes in 2050. (IEA 2021a: 44)

In 2019, the share of internal combustion engine vehicles (ICEs) in total transport-related greenhouse gas emissions in Austria was almost 99%, making the decarbonisation potential that prevails here obvious. (Austrian Umweltbundesamt 2021: 122, 124) The dominance of combustion engines will dwindle in the coming years and decades, the transition phase has already been initiated, and last but not least, political requirements also ensure that combustion engines will no longer have a long-term future, at least in passenger transport. For example, in July 2021 the European Union submitted a proposal to ban the sale of diesel or gasoline cars. (Reuters 2021: online) In addition, some of the vehicle manufacturers are setting even more ambitious targets. For example, Fiat, Ford, and Volvo have announced that they will no longer sell vehicles with combustion engines from 2030 onwards. More and more car manufacturers are communicating clear targets in this respect. (ICCT 2021: 2) This transition is still based almost exclusively on a switch from combustion engines to battery electric vehicles (BEVs), as can be seen from the

new registrations of the individual vehicle technologies. (Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie 2021b: 5) However, a 100% substitution of combustion engines by electric cars seems hardly conceivable. Particularly in the case of heavy-duty traffic, current technology requires batteries that account for a significant proportion of the total weight in order to be able to achieve ranges that are approximately similar to those of diesel-powered vehicles, for example. (Cunanan et al. 2021: 5) In this context, the long charging times compared to refuelling with diesel, gasoline or hydrogen are clearly a disadvantage. (Staffell et al.: 3)
Another aspect is the enormous demand for raw materials such as lithium, nickel, cobalt, manganese, and graphite, which can lead to problems in the supply chain as well as to a less positive environmental balance of an electric car. (Jones et al. 2020: 2) From today's perspective, it is therefore more than unlikely that electric cars will be the sole saviour for decarbonising the transport sector in Austria. Particularly in the case of the heavier commercial vehicles mentioned, comfort, range and charging time advantages are powerful arguments in favour of fuel cell electric vehicles (FCEVs) finding their place in Austria's vehicle mix alongside battery-powered cars. (Shell 2017: 50)
The IEA, as one example, identifies green hydrogen as a piece of the puzzle to achieve the global net zero emissions goal by 2050. (IEA 2021a: 19)

The aim of this master thesis is to explain the potential and limitations of green hydrogen to contribute to the decarbonisation of the Austrian transport sector. This will be done through a more in-depth analysis of i) light-duty vehicles (LDVs), ii) light commercial vehicles (LCVs), iii) medium commercial vehicles (MCVs) & heavy commercial vehicles (HCVs) and iv) buses. For this purpose, the following structure was chosen.

Chapter 2 "background information" discusses, among other things, the share of transport in Austria's total greenhouse gas emissions and how this is divided between the four individual vehicle segments. In order to shed light on the role of green hydrogen, the different types/colours of hydrogen and the most important technologies in the production of green hydrogen are presented. This is followed by a section on the current costs of the production of green hydrogen as well as the current costs of fuel cell electric vehicles in order to give a picture of the economic viability of green hydrogen or a car with a fuel cell. This chapter concludes with an outline of the political measures to promote hydrogen in Europe and Germany and their implications for Austria.

Chapter 3 deals with the chosen methodology of this master thesis and includes, among other things, the literature research, data sets used, expert interviews and models applied. The latter point in particular is one of the most important cornerstones of this thesis. Among other things, models for calculating the total cost of ownership (TCO), in particular, the GREET® Model for calculating the CO_2 emissions of the individual vehicle technologies and types are explained and it is described how the CO_2 savings potential of fuel cell electric vehicles in Austrian traffic can be calculated with the help of GREET. GREET stands for Greenhouse gas, Regulated Emissions, and Energy use in Transportation.

Chapter 4 starts with the most basic questions to be answered in Chapters 4 and 5. This includes an evaluation to what extent green hydrogen can be an economic argument in the coming years. Subsequently, (i) the current production costs of green hydrogen as well as the future development of production costs are examined, (ii) a TCO comparison of the current and future costs of fuel cell electric vehicles, battery electric vehicles and vehicles with internal combustion engines for the for the 4 vehicle segments in the focus of this master thesis is performed (iii) and the three different growth scenarios for FCEV fleet development, which serve as the basis for the calculations in Chapter 5, are outlined.

Chapter 5 then uses the GREET® model, among other things, to calculate the CO_2 savings potential of FCEVs in the Austrian transport sector. In addition, a calculation of the required additional amounts of green electricity resulting from the three FCEV growth scenarios is performed, with a subsequent evaluation of the resulting findings.

The last chapter, chapter 6, contains the conclusions as well as an outlook resulting from the findings of this master thesis.

2. Background information

2.1 Greenhouse gas emissions breakdown in Austria

In Austria, greenhouse gases (GHG) amounting to 79.8 mn tonnes of CO_2 equivalents (t CO_2eq) were emitted in 2019. Compared to 1990 - this year serves as the basis for the European Commission's CO_2 reduction target of 55% in 2030 ("Fit for 55") - this means an increase of 1.8%, even though a decrease of 12.1 t CO_2eq (-13.4%) has been registered since 2005. (Austrian Umweltbundesamt 2021: 6, European Parlament 2021: 2)

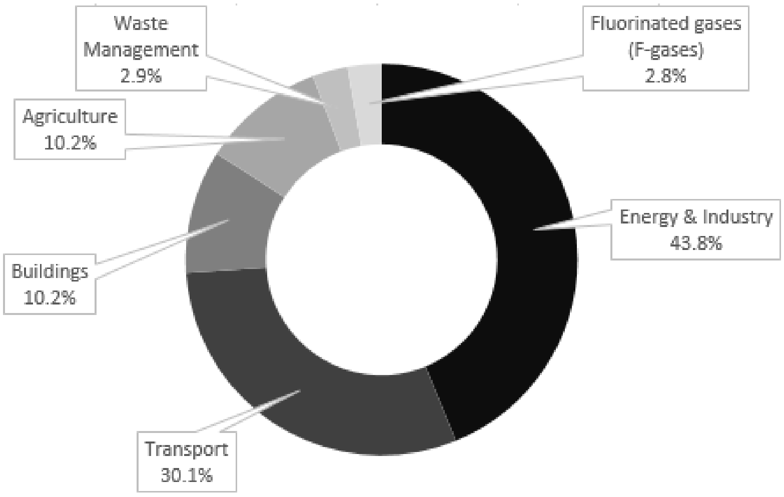

Figure 5: Share of sectors in GHG emissions in 2019 (Austrian Umweltbundesamt 2021:70, 230)

As illustrated in Figure 5, the energy and industry sectors cause the most greenhouse gas emissions in 2019 with a share of 43.8% of total greenhouse gas emissions (including emissions trading). The transport sector follows relatively close behind with a share of 30.1%. Buildings accounted for 10.2%, agriculture 10.2%, waste management 2.9% and fluorinated gases (F-gases) 2.8%. (Austrian Umweltbundesamt 2021: 70)

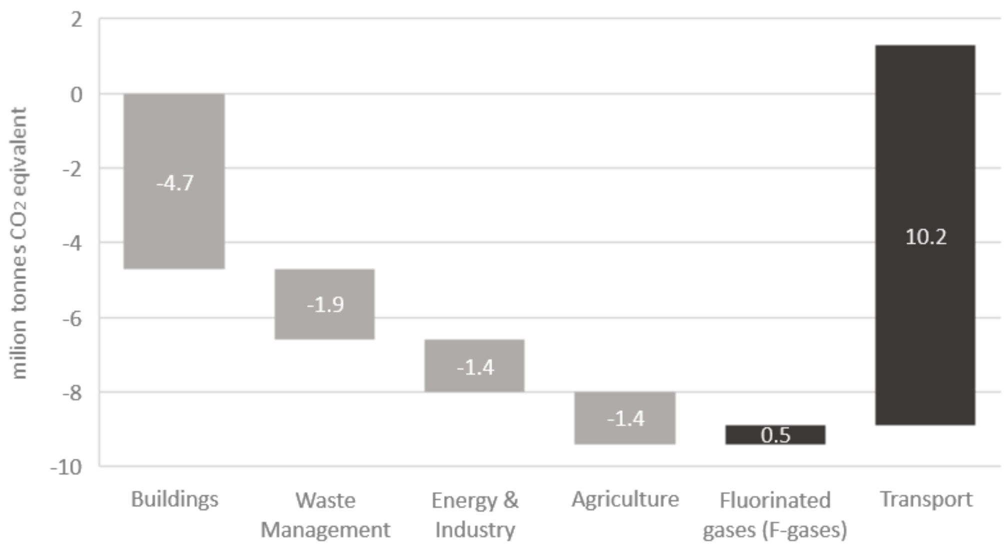

Figure 6: Change in emissions between 1990 and 2019 in Austria (Austrian Umweltbundesamt 2021: 70, 230)

Figure 6 shows that emissions savings were achieved in most sectors over the period from 1990 to 2019. Buildings were able to reduce their total greenhouse gases by 4.7 mn t CO_2eq or more than 36%. This was followed by waste management with -1.9 mn t CO_2eq (-45%), energy & industry with -1.4 mn t CO_2eq (-4%) and agriculture with -1.4 mn t CO_2eq (-15%). F-gases showed a slight increase with 0.5 mn t CO_2eq (+29%). Transport exhibited by far the most negative development with an increase of 10.2 mn t CO_{2eq} (74%).

Road transport is currently still largely dominated by fossil fuels. In 2019, it was responsible for 29.6% or 23.7 mn t CO_2eq. Passenger transport (cars, mopeds, buses, and motorcycles) accounted for 18.7% or 14.9 mn t CO_2eq, while freight transport (heavy and light commercial vehicles) accounted for 11.0% or 8.7 mn t CO_2eq. (Austrian Umweltbundesamt 2021: 124)
Diesel (53.1%) and gasoline (42.9%) dominate the vehicle population in the passenger car sector as of 30 October 2021. BEVs still play a very minor role with 1.4%. Hybrids like plug-in hybrid electric vehicle (PHEV), in particular diesel and gasoline PHEVs account for about 2.5%. The total number of fuel cell electric vehicles in Austria was only 57 and thus does not make it into the ranking statistically. (Statistics Austria 2021: 1)

Hydrogen has not yet played a significant role in the transport sector. (IEA 2021a: 43) In the course of the EU's goal of climate neutrality by 2050, or in Austria's case already by 2040, and the EU deal, which provides for a 90% reduction in greenhouse gas emissions in the transport sector by 2050, green hydrogen could also play an important role in the transport sector from the middle of the next decade, but at the latest in the period 2041-2050. (European Commission 2019: 10; Republic of Austria 2020: 73) In order to shed more light on this, it seems useful to first explain a few basic aspects about hydrogen.

Hydrogen itself is the most abundant element in our universe, with a mass fraction of about 75%. On our planet, hydrogen occurs mainly in bound form in combination with oxygen in the form of water or water vapour. In terms of weight, water is composed of 11.2% hydrogen and 88.8% oxygen. (Shell 2017: 7)
Hydrogen is an energy carrier. It is already used in various areas of the economy in a wide variety of forms, e.g. in the industry, transport, power, or buildings sectors. (European Commission 2020a: 1)

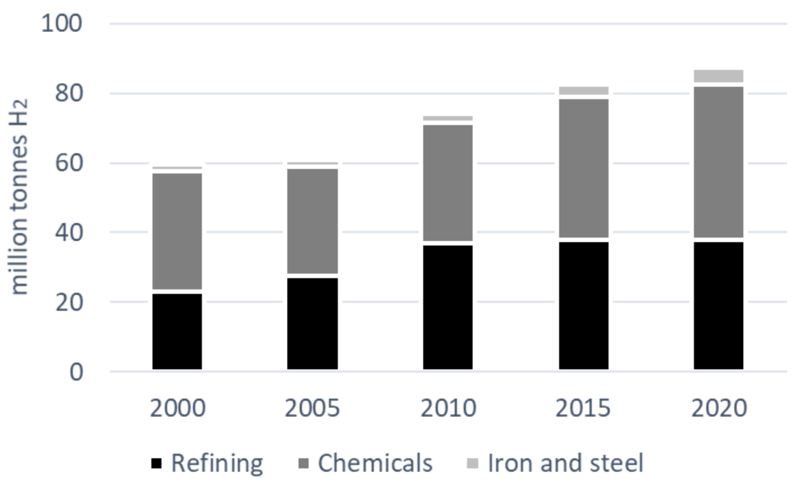

Figure 7: Hydrogen demand by sector, 2000-2020 (IEA 2021a: 43)

Figure 7 shows the development of hydrogen demand over the last 20 years and which sectors are responsible for it. Accordingly, the global demand for hydrogen has increased since the year 2000 by about 50% to almost 90 mn tonnes in 2020.

The chemical sector accounted for about half with a consumption of 45 mn tonnes in 2020, most of it as feedstock for ammonia, followed by methanol. The refining sector represents by far the second largest sector with around 40 mn tonnes and most of the remaining share is attributable to the direct reduced iron process in the steel sector. (IEA 2021a: 43) The transport sector, on the other hand, still plays a very minor role for hydrogen. From a technological point of view, however, hydrogen also fulfils the prerequisites for playing a noteworthy role in the vehicle segment or in shipping and aviation. (European Commission 2020a: 7)

As mentioned, hydrogen is predominantly found only in bound form. This in turn means that it must be produced to be used for chemical or energetic purposes. Hydrogen can be produced from a range of energy sources such as natural gas, coal, oil, biomass and electricity from renewable energy or nuclear power. (IEA 2021a: 14) There are various processes for the production itself. In this context, one also speaks of the colour theory of hydrogen.

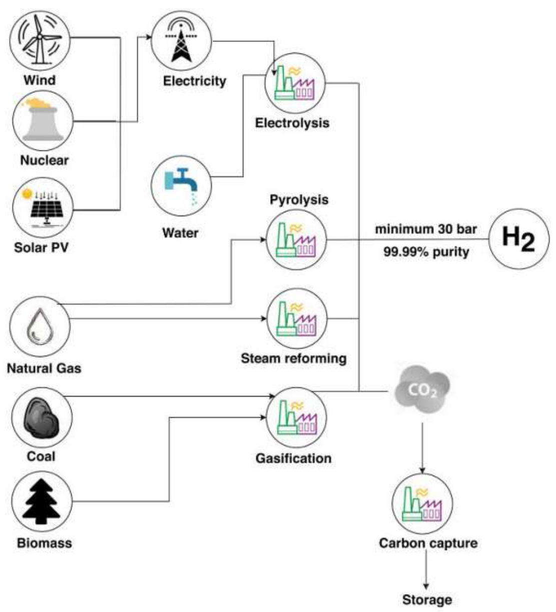

Figure 8: Production processes considered to produce 1 kg of H_2 at a minimum of 30 bar and 99.99% purity (Amjad Al-Qahtani et al 2020: 5)

Figure 8 shows the possible production paths for the production of hydrogen. The absolute majority of hydrogen produced today is called grey hydrogen. This is already produced in commercial quantities by means of gas in the steam methane reforming (SMR) process. Coal or biomass, for example, can also be used in a gasification process. Due to the characteristics of the energy sources used, this process results in a considerable amount of CO_2 emissions.

Blue hydrogen works on the same principle as the SMR process or the gasification process, with the difference that carbon capture and storage is used here, which means that the gas used for production is separated and stored during extraction. However, this process is not 100% efficient. As of April 2021, there were only two commercial plants in the world producing blue hydrogen (operated by Shell in Alberta and Air Products in Texas). From these data, CO_2 capture rates ranged from 53 to 90%. (Howarth et al. 2021: 2 and 5) In contrast, the oil and gas company Equinor sees significantly higher capture rates and states the following in this context: "in all our hydrogen projects, Equinor targets a minimum CO_2 capture rate of 95%, but we assess whether a higher capture is feasible for the respective project and framework conditions. Based on ongoing work with technology suppliers, we believe 98-99% CO_2 capture rate is technically possible." (expert interview with Equinor, February 2022) It should be mentioned here that in the case of Austria, the storage of CO_2 in the form of Carbon Capture & Storage (CCS) has been prohibited since 2011. In 2019, the federal government confirmed that it sees no need to change this federal law, even after a reassessment of this technology. (Bundesministerium für Nachhaltigkeit und Tourismus 2019: 4, 9)

To qualify as green hydrogen, electrolysis is used to split water, or more precisely water molecules, into hydrogen and oxygen. (Lamy et al. 2020: 9) Moreover, the electricity required must be generated from renewable energy sources and thus be CO_2-free. (IRENA 2020a: 9)

If the focus is now on green hydrogen - as in this master thesis - the electrolysis process is used. (IRENA 2020a: 9) With an increasing demand for green hydrogen, the demand for renewable energies for the production of hydrogen clearly increases. The amount required to produce 1 kg of hydrogen, for example, depends primarily on the efficiency of the electrolysers used. Depending on the technology used, the efficiency varies. (Lamy et al. 2020: 30)

Currently, three different technologies are used in this context: alkaline electrolysis, proton exchange membrane (PEM) electrolysis and solid oxide electrolysis cell (SOEC). In 2020, alkaline electrolysers had the largest market share with 61%, followed by PEM electrolysers with 31%. (IRENA 2021: 116) Alkaline electrolysis has been used for hydrogen production since the 1920s and is therefore considered a mature technology. PEM electrolysis was first used in the 1960s and is still used mainly for smaller applications. SOEC electrolysis is the least proven technology and until a few years ago only tested under laboratory conditions. (Schmidt 2017: 2) In 2020, SOEC capacities were only 0.8 megawatt (MW) out of a total of around 290 MW. (IEA 2021a: 116)

Table 1: Techno-economic characteristics of different electrolyser technologies (IEA 2019a: 44)

	Alkaline electrolyser			PEM electrolyser			SOEC electrolyser		
	today	2030	long term	today	2030	long term	today	2030	long term
Electrical efficiency (%, LHV)	63-70	65-71	70-80	56-60	63-68	67-74	74-81	77-84	77-90
Operating pressure (bar)	1-30			30-80			1		
Operating temperature (°C)	60-80			50-80			650 -- 1,000		
Stack lifetime (operating hours)	60,000 -- 90,000	90,000 -- 100,000	100,000 -- 150,000	30,000 -- 90,000	60,000 -- 90,000	100,000 -- 150,000	10,000 -- 30,000	40,000 -- 60,000	75,000 -- 100,000
Load range (%, relative to nominal load)	10-110			0-60			20-100		
Plant footprint (m^2/kW_e)	0.095			0.048					
CAPEX (USD/kW_e)	500 -- 1,400	400 -- 850	200 -- 700	1,100 -- 1,800	650 -- 1,500	200 -- 900	2,800 -- 5,600	800 -- 2,800	500 -- 1,000

Table 1 shows the three electrolyser technologies mentioned above and their main techno-economic differences. In terms of efficiency, SOEC electrolysers achieve the highest efficiency rates of 74-81%. In the long term, the IEA expects an increase to 77-90%. Alkaline electrolysers achieve 63-70% here with a long-term potential of 67-74%. In the case of PEM electrolysers, the current figure is 56-60%, with an increase to 67-74% expected in the longer term. (IEA 2019a: 44) However, expert interviews with ITM Power and NEL have shown that the efficiency of alkaline and PEM are now in some cases significantly above the levels specified in this table compiled in 2019. ITM Power puts the efficiency of a PEM electrolyser at a value of up to 77%. (expert interview with ITM Power, December 2021) In the literature, ranges of 80-85% for PEM systems and 70-75% for alkaline systems can be found. (Perez et al. 2021: 2)

When it comes to producing highly compressed hydrogen with the electrolyser technologies listed, it is shown that PEM electrolysers are capable of producing very highly compressed hydrogen at 30-60 bar, while hydrogen produced with alkaline or SOEC only reaches 1-30 bar and 1 bar, respectively. The operating temperature of SOEC electrolysers is 650-1,000 °C, which is significantly higher than that of alkaline (60-80 °C) and PEM electrolysers (50-80 °C). The lifetime of the stacks for alkaline electrolysers is 60,000-90,000 operating hours and could increase to 100,000-150,000 in the long term. For PEM electrolysers, it is currently 30,000-90,000, with the prospect of 100,000-150,000 operating hours. In the case of SOEC electrolysers, these are currently much lower than those of alkaline and PEM with 10,000-30,000 operating hours. In the long term, however, the gap could be closed somewhat with 75,000-100,000 operating hours. In terms of load range, there are no significant differences for the three technologies alkaline (10-110%), PEM (0-160%) and SOEC (20-100%). At around 0.095 square metre/kilowatt-electric (m_2/kW_e), alkaline electrolysers have almost twice the plant footprint of PEM with 0.048 m_2/kW_e. The costs for alkaline electrolysers are currently USD 500-1400/kWe. According to the IEA, these will roughly halve in the long term to USD 200-700/kW_e. PEM electrolysers are currently more expensive at USD 1,100-1,800/kW_e but may converge to alkaline electrolysers in the more distant future at USD 200-USD 900/kW_e. The highest costs are currently found in SOEC electrolysers at USD 2,800-5,600/kW_e, but these should be reduced significantly to USD 500-1,000/kW_e in the longer term. (IEA 2019a: 44)

Overall, the operational production costs of hydrogen (excluding CAPEX for an electrolyser) are primarily dependent on the efficiency of the electrolyser plant.

The energy efficiency is calculated as follows:

$$\eta e = \frac{HHV_{H_2}}{E_S} \tag{1}$$

where ηe is the energy efficiency (percent), HHV_{H_2} is the higher heating value of hydrogen (kilowatt hour (kWh) per kg), and E_S is the specific energy consumption/electricity requirement (kWh/kg)
(Cavliere et al. 2021: 11)

The HHV stands for the energy required to produce 1 kilogramme of H_2 at an energy efficiency of 100% and is 39.4 kWh/kg. If the electrolysis plant now has an efficiency of 70%, this means that approx. 56 kWh are required to produce 1 kg of hydrogen. (Cavliere et al. 2021: 11) Accordingly, depending on the demand for green hydrogen, the required amount of renewable energy can be calculated.

From a technological point of view, PEM technology has several advantages over alkaline technology. Faster start-up times, no corrosion, easier maintenance, and fewer components argue for PEM electrolysis, while the lower cost of alkaline technology is a strong argument for alkaline electrolysis. (Guo et al. 2019: 5)

Due to the more expensive components of PEM technology such as platinum, iridium and titanium, the costs of this technology are currently USD 1,750/kW_e, higher than those of alkaline electrolysis at USD 1,000-1400/kW_e. In China, these are already said to be as low as USD 500/kW_e, although there are concerns about reliability and durability compared to Western alkaline electrolysers. (IRENA 2021: 116, 120) From ITM Power's point of view, the argument of higher costs for PEM technology is primarily due to the fact that aspects such as lower maintenance costs or a higher purity of the produced hydrogen are not included in the analyses. (expert interview with ITM, December 2021)

Due to the very low total capacities of all three technologies to date, it can be assumed that costs will still fall significantly as a result of economies of scale. (IRENA 2020b: 8)

In one of its studies, IRENA considers it realistic that capacities measured in terms of those already under construction and in planning could increase from the current 290 MW to 54 gigawatt (GW) as early as 2030. (IEA 2021a: 116 and 117) Clearly, these are greatest for the technologies that that have so far achieved the least market maturity. (Schmidt et al. 2017: 12)

In the case of PEM electrolysis systems, the literature usually assumes a learning rate of between 15% and 21%. (IRENA 2020b: 78)

Uncertainties in these assumptions cannot be ignored, of course. The uncertainties in these assumptions are of course not negligible. The lack of predictability about the direction in which the prices of finite raw materials such as platinum, iridium or titanium will develop makes this even more obvious. (IRENA 2020b: 52)

Bristowe and Smallbone have calculated in a study on the cost reduction potential in hydrogen production that PEM electrolyser costs could fall by about 70% if capacities were increased tenfold. (Bristowe G. et al. 2021: 15, 16)

2.2 Factors influencing the costs of hydrogen

The costs for the production of hydrogen vary greatly depending on the production process but are very likely to converge over the next years and decades due to technological progress and the learning curve. The two most significant cost factors in the production of hydrogen are the investment costs for the production plant (e.g. electrolyser, reformer) and the electricity feed stock. The latter often have an even greater impact compared to the investment costs. Operation & Maintenance (O&M) costs account for a smaller part. (IEA 2021a: 113)

The aforementioned costs for the electricity from renewable energies required for the production of green hydrogen have fallen significantly in recent decades. In the meantime, even without subsidies, these costs are in many cases lower than those of electricity production based on fossil fuels or nuclear energy. (IEA 2021b: 333)

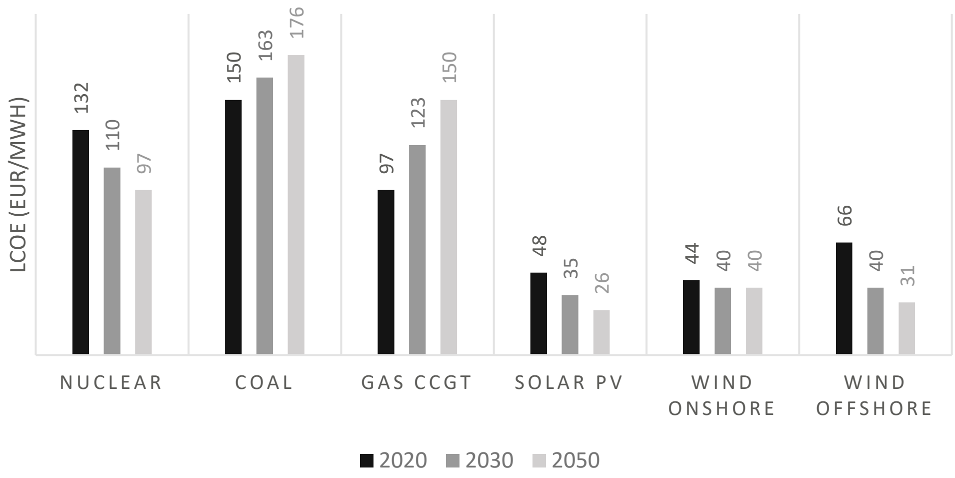

Figure 9: Technology costs in Europe according to STEPS (IEA 2021b: 333)

Figure 9 shows the evolution of levelized cost of electricity (LCOE) for the different energy sources in Europe according to the Stated Policy Scenario (STEPS) defined in the IEA's World Energy Outlook 2021. This scenario includes the current policy framework and is based on an assessment of all the sectors and the existing policies and those already announced by governments. (IEA 2021b: 16) It assumes that the cost of solar PV in Europe will decrease by about 45% to EUR 26 per megawatt hour (MWh), onshore wind by 9% to EUR 40/MWh and offshore wind by more than 50% to EUR 31/MWh in 2050 compared to 2020 (based on a EUR/USD exchange rate of 1.1326 as of 31.12.2021, ECB 2022: 1). This means that even under the IEA's least ambitious scenario for combating climate change, the cost advantage of renewables over coal - LCOE for coal are expected to increase from EUR 150 to EUR 177/MWh - and gas CCGT (combined cycle gas turbine) – LCOE expected to increase from EUR 97 to EUR 150/MWh - would be extended both in absolute and relative terms by 2050. Compared to nuclear power, which is also a form of CO_2-free electricity generation, its projected drop from EUR 132 to EUR 97/MWh would at least increase the relative cost advantage of solar PV and offshore wind. (IEA 2021b: 333) A comparison of renewables with coal or gas in the "Net Zero Emissions by 2050 Scenario" developed by the IEA would be obsolete in this scenario, since these two energy sources would no longer be relevant in 2050. Compared to nuclear, LCOE of solar

PV and offshore wind in this scenario would be 78% lower at 22 EUR/MWh compared to 102 EUR/MWh for nuclear. (IEA 2021b: 336)

A more detailed analysis of the production costs of green hydrogen is given in Chapter 4.

2.3 Economics of fuel cell electric vehicles

The situation with fuel cell electric vehicles is that, on the one hand, there are still very few market-ready models on the market and, on the other hand, the costs are still very high due to the low production figures compared to vehicles with combustion engines, but also to battery-powered cars. At the end of 2020, there were just 34,800 FCEVs worldwide. Of these, around 75% were light-duty vehicles (LDVs), 15% were buses and 10% were trucks (99% of trucks exist in China). However, growth rates averaged 70% from the end of 2017 to the end of 2020, although this rate reduced to 40% in 2020. (IEA 2021a: 36) In the six months to the end of June 2021, the number of FCEVs increased by more than 8,000 to just over 43,000. (IEA 2021a: 69) South Korea had the most FCEVs at the end of 2020, followed by the US, China, Japan, and Germany. (IEA Technology Collaboration Programme 2021: 4) In Austria, there were just 45 FCEVs on the roads at the end of December 2020. (Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie 2021a: 5)

Comparing battery-powered cars with FCEVs, the same but also different aspects can be identified that stand in the way of faster growth. In the case of BEVs, the short range, the significantly longer charging times compared to ICEs and FCEVs, but also the initial capital costs and the infrastructure are the greatest prerequisites. In the case of FCEVs, on the other hand, it is often the lack of economic viability due to high initial capital costs, an insufficiently available infrastructure, high fuel costs and the very different ambitious political goals of individual countries that have prevented a breakthrough for fuel cells to date. (Ajanovic et al. 2020: 2,7,8)

The issue of infrastructure reveals the often-discussed chicken-and-egg problem. (DeCicco 2004: 1) While 15 hydrogen refuelling stations (HRS) are able to provide the same throughput as 900 BEV fast-chargers, this does not solve the low geographic coverage compared to BEVs. (Staffell et al. 2019: 4) Until the infrastructure is sufficiently in place, the low convenience factor does not allow a critical mass of customers to be willing to purchase an FCEV. The operators of HRS, on the other hand, do not see an economic case to significantly expand their network of refuelling stations now, which would be necessary to increase the convenience factor of FCEV owners. Nikola, a manufacturer of FCEV trucks, sees the solution in the need to control both sides as a company, i.e. the company does not only act as a manufacturer of FCEVs, but also pushes the construction of HRSs. (expert interview, December 2021) Honda Motor, on the other hand, sees the establishment of interest groups such as the Hydrogen Council, which was founded in 2017, as a way to both reduce the cost of producing an FCEV in the future and to accelerate the development of the infrastructure. In addition, in Honda's case, there is close cooperation with the government to ensure a cheap supply of hydrogen. (expert interview with Honda Motor, December 2021) Referring to the last point, policy makers in some countries have also recognized this problem. Leading the list is Japan, which has set a target of 900 HRS by 2030, followed by South Korea with a target of 1,200 HRS by 2040 and France with 400-1,000 HRS by 2028. (IRENA 2021: 28; Korean Ministry of Trade, Industry and Energy 2019: 8; Ministère francais de la transition écologique 2018: 13) Numerous other countries, such as Germany, have defined specific targets in their National Hydrogen Strategy regarding the expansion of their electrolysis capacities, in Germany's case of 5 GW by 2030 - but no specific defined targets regarding HRS. (Bundesministerium für Wirtschaft und Energie 2020: 5, 20, 23) At the end of 2020, there were about 540 HRS worldwide, most of them in Japan ahead of Germany, China, USA, and South Korea. (IEA Technology Collaboration Programme 2021: 15) In South Korea the ratio of FCEV to HRS is 200:1, in the USA 150:1, in Japan just 30:1. In comparison, the ratio for gasoline/diesel vehicles is 1,800:1 (IEA 2021a: 70) At the end of December 2021 there were only 5 hydrogen refuelling stations in Austria and 55 FCEVs on its roads. (https://h2.live/ 2021; expert interview with OMV, November 2021; Statistik Austria 2022: 2) This results in a ratio of FCEVs to HRS of only 11:1, but the absolute number of refuelling stations is still too low to stimulate the growth of FCEVs.

Fuel costs and infrastructure play an important role in the purchase of an FCEV. However, the most important factor in the passenger car sector is probably the cost of the fuel cell vehicle itself. There are two ways of looking at this. The first is the initial investment costs, the second is the total cost of ownership (TCO). TCO is defined as "a purchasing tool and philosophy which is aimed at understanding the true cost of buying a particular good or service from a particular supplier" (Ellram 1995: 1) The TCO approach includes both the purchase price of the FCEV and the operational costs. (Argonne National Laboratory 2021: xvii)

Studies have shown that the TCO approach - although the economically more rational one - is only applied to a limited extent for the majority of car buyers of passenger cars. Thus, in the decision-making process on the purchase of a car, the fuel economy, among other things, may not be given the importance it deserves from an economic point of view. This may be due to a lack of information or insufficient knowledge of mathematics on the part of the car buyer, or a prioritisation of other aspects such as performance and applications, which prevents a rational purchase decision from an economic point of view. (Hagman et al. 2016: 2; Greene et al. 2013: 1)

For commercial customers, on the other hand, TCO is considered to be the absolutely dominant basis for decision-making (expert interview with Nikola Corporation, December 2021)

2.4 Environmental footprint of green hydrogen and FCEV

The most obvious resource in the production of green hydrogen by electrolysis is water itself. The theoretical minimum is 9 litres of water to produce 1 kg of hydrogen. In most cases, however, the consumption is around 25% higher (Shi et al. 2020: 2). There are also differences in water consumption between the various technologies. In the case of PEM technology, this is usually significantly higher than that of alkaline technology. (Simoes et al 2021: 3; European Commission 2020: 216) Water consumption in particular has become much more important in recent years in terms of the ecological aspect. (Mehmeti et al 2018: 3) Specifically, the fact that larger amounts of fresh water are needed here and part of it cannot be recovered. However, the part that cannot be recovered is the significantly smaller one. In a study by Beswick et al. it is calculated that if hydrogen were consumed 25 times more than it is today, and assuming that hydrogen is produced solely by electrolysis, the amount of unrecoverable water would be 0.3 ppm of the world's available fresh water. (Breswick et al. 2021: 2)

The most obvious advantage of an FCEV over an ICE is that it emits no greenhouse gas emissions at the point of use. (Ajanovic et al. 2020: 8) If it is green hydrogen, which is also fed exclusively with electricity from renewable energies throughout the well-to-tank (WTT) supply chain, then the only CO_2 emissions that occur are from the vehicle cycle, i.e. production, assembling, decommissioning and recycling. In the case of ICEs, on the other hand, emissions are produced along the entire life cycle. (GREET 2021)

While no CO_2 emissions are caused in the production process of green hydrogen, the various electrolyser technologies (alkaline, PEM, SOEC) are subject to a far more critical examination. A study by Mori et al. names platinum as the metal with by far the greatest environmental impact in PEM technology. In the case of alkaline technology, nickel has the greatest negative impact, while in the case of SOEC technology nickel, together with some other materials, also has a very negative screen. (Mori et al. 2021: 2, 17-23) According to the European Commission, Europe is in a strong dependency in the case of 19 out of 29 metals relevant for fuel cells and electrolysers. (European Commission 2020b: 10)

However, it should also be noted here that it can be assumed that technological progress will also reduce the demand per kW_e. In the case of platinum, Deloitte calculates in a study that the amount of platinum required will fall from 0.4-0.5 gram (g) per kW_e in 2020 to 0.2g/kW_e in 2030. (Deloitte 2020: 12)

2.5 Implications of the hydrogen policy of the EU and Germany for Austria

The European Commission presented its hydrogen strategy in July 2020. Figure 10 shows the targets of the capacity expansions for hydrogen production. These include an expansion of the current capacities of just over 100 MW in 2020 to at least 6 GW and at least 40 GW in 2024 and 2030 respectively.

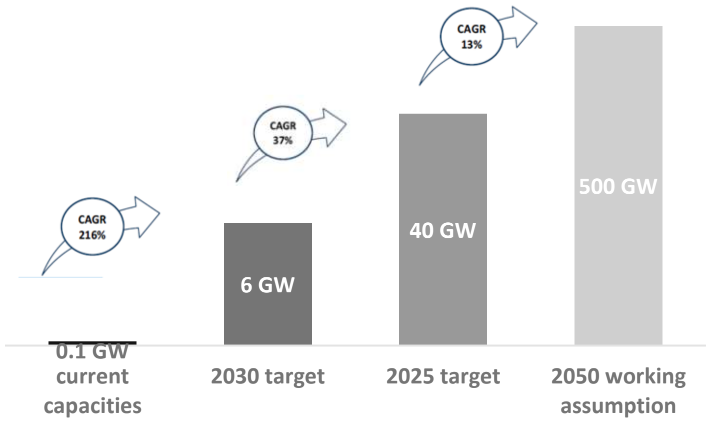

Figure 10: EU hydrogen strategy (European Commission 2020a: 5,6,8), IEA 2021a: (116)

The compounded annual growth rate (CAGR) is therefore 37% from 2024 to 2030. (European Commission 2020a: 5-8, IEA 2021a: 116) CAGR reflects constant year-on-year growth over a given period. (Payumo et al. 2019: 10) For 2050, a working assumption of the EU Commission foresees capacities totaling 500 GW. This still corresponds to a double-digit CAGR of 13% in the period from 2030 to 2050. (European Commission 2020a: 5,6,8; IEA 2021a: 116)
With these capacities, up to 1 mn tonnes of green hydrogen are to be produced in 2024, and up to 10 mn tonnes in 2030. Political support will also come from EU funds and EIB financing. A total of EUR 24 billion to EUR 42 billion (bn) is to be invested in hydrogen projects by 2030. In order to supply these projects with renewable energy, the European Commission estimates that a further EUR 220 bn to EUR 340 bn will need to be invested in solar and wind capacity. Another EUR 65 bn is considered necessary for hydrogen transport, distribution, and storage as well as for hydrogen refuelling stations (HRS). By 2050, a total of EUR 180 billion to EUR 470 billion is to be invested in the expansion of hydrogen production capacities. (European Commission 2020a: 5-8, IEA 2021a: 116)

At the time of completion of this master thesis, no hydrogen strategy of the Austrian Federal Government was available, although the publication of such a strategy was originally announced for 2021. In order to determine the demand for hydrogen in Austria, it seems reasonable to refer to the existing National Hydrogen Strategy of

Germany (NHS) and to derive Austria's demand from it. The Austrian GDP in 2020 was about 11% of the GDP of Germany. (UNECE 2021: online) The Federal Republic of Germany has calculated in its NHS that there is a hydrogen demand of 90 to 110 terawatt hours (TWh) in Germany until 2030. For this purpose, generation plants of up to 5 GW are to be built during this period. These capacities correspond to a green hydrogen production of 14 TWh and a renewable energy demand of 20 TWh. By 2035, at the latest by 2040, a further 5 GW of capacity is to be added. Of these up to 5 GW, 2 GW are to be allocated to transport in 2030. This in turn corresponds to a production of green hydrogen of 5.6 TWh and a demand for renewable energies of 8 TWh. (National Hydrogen Strategy of Germany 2020: 5, 19) Adapted to Austria, this corresponds to a hydrogen demand of 9 to 11 TWh at an assumed ratio of 1:10. The newly built capacities in Austria would thus amount to up to 500 MW by 2030 or 1 GW by 2035/2040. This would then be equivalent to a production of green hydrogen of 1.4 TWh and a demand for renewable energies of 2 TWh by 2030 or twice this amount by 2035/2040. Converted to the transport sector, this means electrolyser capacities of 200 MW and a green hydrogen production of 560 MWh as well as a demand for renewable energies of 800 MWh by 2030 were to be allocated to transport. The additional electricity demand could easily be covered by the expansion targets for renewable energies of 27 TWh until 2030, which are laid down in the Renewable Energy Expansion Act. (Parliament of the Republic of Austria 2021: 6)

In order to incentivise investment in hydrogen vehicles (passenger cars, heavy-duty vehicles, busses, trains, inland and coastal shipping), subsidies of EUR 3.6 bn are to be made available in Germany by 2023 for the purchase of electrically powered vehicles, for commercial vehicles with alternative, climate-friendly drives and for buses with alternative drives. EUR 3.4 bn is to be made available for a needs-based refuelling infrastructure across all alternative technologies (incl. hydrogen refuelling stations) by 2023. (National Hydrogen Strategy of Germany 2020: 20) As in Germany, it will also be necessary in Austria to provide subsidies or incentives both for the construction of hydrogen refuelling stations and for the purchase of an FCEV. With just 5 hydrogen refuelling stations in Austria, it is not surprising that the number of FCEVs sold is only expanding very slowly. (expert interview with OMV, November 2021)

3) Method of approach

The main purpose of this master thesis is to analyse the potential and limitations of hydrogen to decarbonise the Austrian transport sector.

At the beginning of this work, an extensive literature search was carried out, which focused on hydrogen in general, but also on hydrogen as a fuel in the fuel cell. A very strong focus was placed on literature sources that have a very current time reference, since the topics of green hydrogen and fuel cell electric vehicles are subject to constant and very rapid change. In order to meet the demand for up-to-date data, relevant analyses/reports from recognised institutions such as the International Energy Agency (IEA), IRENA, the European Commission, the Austrian Umweltbundesamt, Fuel Cells and Hydrogen Joint Undertaking (FCH JU) and the financial service provider Bloomberg New Energy Finance (BloombergNEF) were also used.
In addition, expert interviews were conducted. These serve on the one hand to get a better understanding of the current technological status and the future development as well as the current and future costs for the production of green hydrogen and fuel cell electric vehicles. For this purpose, discussions were held with CEOs, CFOs and investor relations teams of companies from the e-mobility sector (Nikola Corporation, Volvo, Daimler Trucks, Honda Motor Company), with electrolyte producers (NEL, ITM Power) and energy companies (Equinor, OMV, Scatec).

Chapter 4 begins by discussing the key topics that need to be answered in order to analyse the potential and limitations of hydrogen in the form of a fuel cell-based transport sector with regard to decarbonisation. For this purpose, sub-chapter 4.2 shows to what extent the production of green hydrogen is or will become economically viable compared to the production of "grey" or "blue" hydrogen. In order to illustrate this, data from the literature as well as from Fuel Cells and Hydrogen Observatory (FCHO) and the financial service provider BloombergNEF (report on "2H 2021 hydrogen levelized cost update") are used. The focus is on the two most important cost factors in the literature, investment costs for electrolysers

and the costs for the electricity from renewable energies required for the production of green hydrogen. (IRENA 2021: 46) In the analysis of the costs for electrolysers, the two technologies determining the market - alkaline and PEM - are analysed. In a second step, the current and expected future total production costs of green hydrogen are compared to those of "blue" and "grey" hydrogen.
Based on data from the Fuel Cell and Hydrogen Observatory (FCHO), the current costs for hydrogen, measured as the levelized cost of hydrogen ($LCOH_2$), are examined and future cost reduction potentials are analyzed. This is done with the help of learning rates for electricity production from wind and solar PV and for electrolysers, respectively, taken from the literature and from specialized institutions. These results are then compared with forecasts from BloombergNEF and other studies.

The determination of the economic viability of FCEVs is based on data from literature and expert institutions (BloombergNEF's "Hydrogen: Fuel Cell Vehicle Outlook", European Commission's paper on "CO_2 standards for new passenger cars and vans" the IEA's "IEA G20 Hydrogen report: Assumptions" and Argonne National Laboratory's report on "Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains"). Specifically, for Europe, the total cost of ownership (TCO) of the four fuel cell vehicle categories LDVs, LCVs, trucks (MCV & HCV) and buses is compared with the costs (EUR per kilometre (km) driven) of a BEV and an ICE of the respective vehicle segment for the year 2030. In addition, the current TCO are also calculated for all vehicles

TCO is calculated as follows:

$$TCO = P + Tax_{car} - S - \left(\frac{RV}{(1+r)^n}\right) + \sum_{n}^{\infty} \left(\frac{Fuel + Tax_{fuel} + I + M}{(1+r)^n}\right) \qquad (2)$$

where TCO is the total cost of ownership (EUR/km), P is the initial purchase price (EUR/km), Tax_{car} is the tax on the car (EUR/km), S is the subsidy for purchasing an FCEV (EUR/km), RV is the residual value (EUR/km), r is the discount rate (in

percent), n is the time of use of the car in years, $Fuel$ is the annual H_2 fueling cost (EUR/km), Tax_{fuel} is the annual tax on fuel (EUR/km), I is the annual insurance costs (EUR/km), and M is the annual maintenance costs (EUR/km)
(Lee et al 2021: 4)

In the calculations of this master thesis, subsidies are taken into account. However, it should be pointed out here that, from today's perspective, there is a high degree of uncertainty as to whether these will still be available at all and, if so, to what extent and for which environmentally friendly technologies in 2030. The exact assumptions for the TCO calculation for the year 2030 can be found in chapter 4.3, those for the current TCO assumptions in the appendix.

Up to this calculation step, no CO_2 tax is taken into account. However, in a TCO comparison that tries to reflect future developments as closely as possible, doing so could certainly contribute to a more realistic cost truth.
Therefore, in a next step (see calculation 3.2), the CO_2 costs (euro cent per km) for ICE vehicles are calculated assuming two different levels of CO_2 prices, once for 2030 and once for 2050. The assumption for the CO_2 price for the year 2030 is based on a forecast of the IEA from its report "Net Zero by 2050 - A Roadmap for the Global Energy Sector". (IEA 2021c: 52) For the year 2050, a forecast by The Network of Central Banks and Supervisors for Greening the Financial System (NGFS) is used. Data from the U.S. Energy Information Administration and the European Commission are used to calculate the CO_2 emissions generated by the ICE vehicles. According to this, 2.2 kg and 2.6 kg of CO_2 are emitted per litre of gasoline and diesel respectively (conversion: 1 gallon corresponds to 3.785 litres). (U.S. Energy Information Administration 2021: online; IEA 2014: 69) This quantity is then multiplied by the respective assumed CO_2 price (EUR/kg). Based on the assumption made by the European Commission in its paper on "CO_2 standards for new passenger cars and vans" that diesel consumption for 100 km is 3.6 litres and gasoline consumption 4.1 litres, the net CO_2 price (in euro cent) per kilometre is calculated. (European Commission 2019: 3) On top of this, a tax applicable to diesel and gasoline is added (assumption of a value-added tax of 20%).

No CO_2 costs are incurred for FCEVs and BEVs, as these two vehicle technologies do not emit any CO_2 at the point of use, as described in Chapter 2. (Ajanovic et al. 2020: 8)
The results can be seen in chapter 4.

The CO_2 amount of total TCO (in EUR/km) is calculated as follows (own formula):

$$TCO_{CO_2} = CO_{2tax} * CO_{2mass} * FC * VAT \tag{3}$$

where TCO_{CO_2} is the CO_2 tax impact on total TCO (EUR/km), CO_{2tax} is the assumed CO_2 price (EUR/kg), CO_{2mass} is the CO_2 emitted per litre of diesel/gasoline (kg/litre), FC is the fuel consumption of a diesel/gasoline vehicle (litre/km) and VAT is the value added tax in percent

The core of this work is the calculation of possible CO_2 savings in the Austrian transport sector through the use of FCEVs based on three different scenarios.
All three scenarios are based on the Austrian Umweltbundesamt vehicle mileage forecasts for the four vehicle segments up to the year 2050, with the following four vehicle categories being the subject of the analysis: i) passenger cars/light-duty vehicles (LDVs), ii) light commercial vehicles (LCVs), iii) medium commercial vehicles (MCVs) & heavy commercial vehicles (HCVs) and iv) buses.
For all these scenarios as well as for the further calculations, 2019 represents the starting year in each case a, the forecasts in turn concern the periods 2030, 2035, 2040, 2045 and 2050, whereby the main focus in the discussion of the results is on the year 2050.

The four different analysed vehicle segments are defined as follows:

i) light-duty vehicles (LDV): these fall into category M1 according to the European classification with the following definition: “vehicles designed and constructed for the carriage of passengers and comprising no more than eight seats in addition to the driver’s seat, and having a maximum mass not exceeding 3.5 tonnes" ACEA (2021b: 1)

ii) light commercial vehicles (LCV): these fall into category N1 according to the European classification with the following definition: “motor vehicles with at least four wheels, used for the carriage of goods and having a maximum mass not exceeding 3.5 tonnes" ACEA (2021d: 1)

iii) medium commercial vehicles (MCV) & heavy commercial vehicles (HCV)

- medium commercial vehicles (MCV): this category belongs to the truck segment, according to the European classification the category is N2 (weight of more than 3.5 tonnes, but less than 16 tonnes) with the following definition: "motor vehicles with at least four wheels used for the transport of goods" ACEA (2021c: 1)
- heavy commercial vehicles (HCV): this category also belongs to the truck segment, according to the European classification the category is N3 (weight of more than 16 tonnes) with the following definition: "motor vehicles with at least four wheels used for the transport of goods" ACEA (2021: 1)

iv) buses: these fall into the M2 (weight less than 5 tonnes) and M3 (weight more than 5 tonnes) categories, respectively, according to the European classification with the following definition: "vehicles with at least four wheels, designed and constructed for the carriage of passengers and having more than eight seats in addition to the driver's seat." ACEA (2021a: 1)

The first scenario on the fleet growth of FCEV is based on the Economic Transition Scenario (ETS) of BloombergNEF and represents the “base scenario”. In this scenario, it is assumed that from 2025 onward, there are no new political measures that contribute significantly to achieving the Paris climate targets. Instead, developments from 2025 onwards are determined by techno-economic trends and market forces. The first step in this scenario is to determine the addressable vehicle market. For this purpose, data from the World Bank for GDP and population growth are used to determine the annual number of kilometres driven for the most important car markets. The TCO is then used to calculate the growth of the various drivetrains. (BloombergNEF 2021b: 17, 190-192)

The second scenario is based on the assumptions of the development of the fuel cell fleet in the individual vehicle segments until 2050, made by the Fuel Cells and Hydrogen 2 Joint Council for their "ambitious scenario". Data from the European Automobile Manufacturers' Association (ACEA) serve as baseline values for the current total fleet of the four vehicle segments in the EU in 2020. (ACEA 2021a: 2, 2021b: 2, 2021c: 2, 2021d: 2) The growth rates for the total fleet up to 2050 are in turn based on data from the European Commission's EU Reference Scenario 2020 (European Commission 2021) for Austria.
This scenario refers to Europe, in which the EU implements the measures necessary to achieve the 2°C target through coordinated efforts on the part of industry as well as politicians and investors. The scenario is based on the Hydrogen Council's Hydrogen Roadmap and has been adapted to Europe. It also draws on data from McKinsey Energy Insights, industry perspectives as well as expert interviews. (Fuel Cells and Hydrogen 2 Joint Councils 2019: 15, 46) The assumptions regarding fleet growth for FCEVs are significantly more optimistic than in the first scenario.

The third scenario, in turn, is based on a "decarbonisation scenario" for global road transport prepared by BloombergNEF. It corresponds to zero tailpipe emission based on the exclusive use of battery-electric as well as fuel cell powertrains, in which hydrogen plays a significant role. Here, individual governments around the world are setting a goal of zero tailpipe emissions based on the exclusive use of BEVs and FCEVs by actively pursuing this and realizing it through appropriate measures. At the same time, hydrogen is also being promoted in other industries for decarbonisation. (BloombergNEF 2020: 2, 21) This scenario reflects a rather hypothetical one, and at the same time includes the scenario with the strongest growth of the FCEV fleet.

All of these scenarios are clearly exemplary scenarios, although the "base scenario" is the one with the highest probability of materialization.

For reasons of simplification, the assumptions on the development of the number of annual vehicle kilometres up to 2050 are the same for all three scenarios, only the distribution of these kilometres among the four vehicle fleet segments changes. This means that the assumption is made that, for example, in 2050 the same number of kilometres will be traveled with an ICE passenger car as would be the case if the vehicle were replaced by a FCEV.

As already mentioned, the annual vehicle kilometres of the individual vehicle categories (LDV, LCVs, MCVs, HCVs and buses) for the period 2019-2050 are taken as the basis for calculating the CO_2 savings potential. (Umweltbundesamt: Results of the Austrian Air Pollutant Inventory 2021) The reason why CO_2 emissions and not GHG emissions are the focus of the calculations is that they are responsible for more than 90% of a vehicle's total GHG emissions. On the other hand, the data coverage with regard to CO_2 data in the literature or at expert institutions is better than that of the total greenhouse gases. Overall, the data evaluation based on the GREET® model used in this analysis also shows that greenhouse gases such as methane (CH_4) or nitrous oxide (N_2O) play a subordinate role compared to transport-related CO_2 emissions, despite their significantly higher global warming potential. (GREET® model data 2021; Bieker 2021: 77)

The CO_2 emissions per vehicle segment are calculated with the help of the GREET® model (version 2021). This model was developed by Argonne National Laboratory with support from the U.S. Department of Energy's (DOE) and is a publicly available tool that provides a comprehensive lifecycle analysis (LCA) or cradle-to-grave analysis (C2G) for the transportation sector, among others. The GREET® model offers the possibility to include many factors in the analysis and has been used in numerous peer-reviewed studies. (Wang et al. 2012: 12) The model provides over 100 different pathways and over 80 vehicle and fuel system technologies. A pathway is a series of processes that comprise the life cycle of a fuel. This varies depending on the resource (e.g. gaseous hydrogen), technology (e.g. gaseous hydrogen production: non-combustion emissions) or processes (e.g. gaseous hydrogen via pipeline produced in central plant from solar energy).

Since the GREET® model is a cradle-to-grave analysis, the respective vehicle technology or vehicle components are also included in the CO_2 balance. Depending on the forecast year, changes in vehicle technology are also taken into account. For example, for calculations of CO_2 emissions for the year 2050, the assumed vehicle technology of the respective vehicle type from the year 2045 (as well as in some cases 2050) was selected.

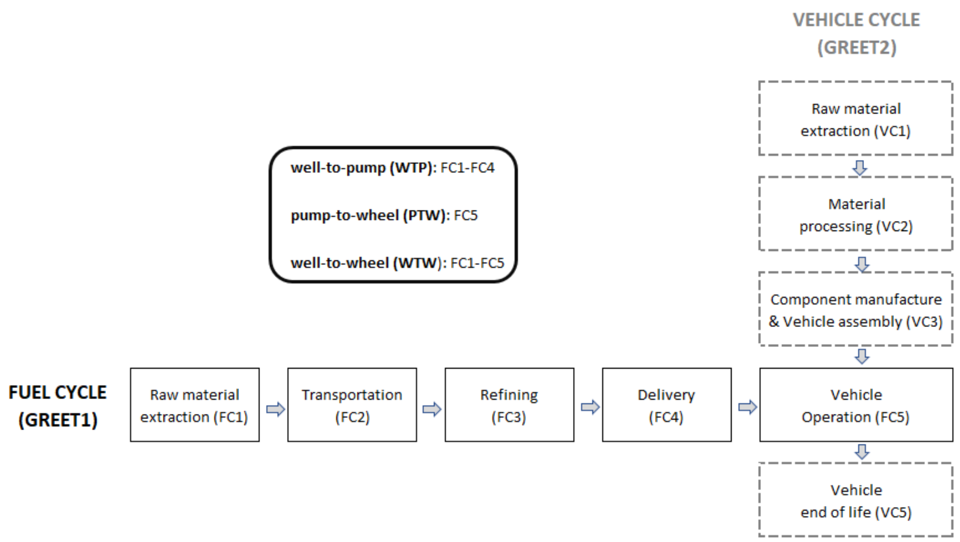

Figure 11: GREET® model (U.S. Argonne National Laboratory 2021: online; Wong et al. 2021: 7)

Figure 11 illustrates the two submodels/process chains that together make up the GREET® model. “Process chain 1” (Greet1) is a so-called well-to-wheel (WTW) analysis. This calculates the total energy consumption and emissions of the entire fuel cycle and includes raw material extraction (FC1), transportation (FC2), refining (FC3), delivery (FC4) and the consumption of fuels during vehicle operation (VC5).

"Process chain 2” (Greet2) in turn calculates the energy consumption and emissions of the vehicle cycle and includes the raw material required for the vehicle (VC1), processing of the vehicle material (VC2), manufacturing and assembly of the vehicle (VC3) and the end-of-life decommissioning and recycling of the vehicle (VC5). (Argonne National Laboratory 2016b: 9, 10, GREET Tutorials: online)

The results of the model show a WTW and a C2G analysis in terms of energy and emissions for the respective vehicle segment. (GREET 2016a: 15) In this master thesis, the reported CO_2 emissions are the relevant parameter for further calculations.

To determine the CO_2 emissions, assumptions were made in the GREET® model for each of the four vehicle segments regarding the following factors: the process used to produce the fuel (pathway), lifetime of the vehicle (km), the weight of the vehicle (tonnes), payload of the vehicle (tonnes), number of passengers (relevant in the case of buses), the proportion of kilometres as a percentage of driven in urban areas.

In addition, however, the model takes into account numerous other factors depending on the vehicle segment selected, such as energy efficiency, combustion, and non-combustion emissions (i.e. brake, tire, wear) in relation to the pollution control system of the car. (GREET® model 2021)

Table 2: GREET® model input data (GREET® model 2021; FCH JU 2020: 66; Toyota 2021: 15; own assumptions)

Vehicle segment	Lifetime (km)	Vehicle weight (tons)	Payload (tons)	Passengers (#)	Urban share (%)	Fuel production pathway
LDV Otto	173,151	1.3	0.10	1	70%	Ref. Gasoline (E10)
LDV Diesel	173,151	1.3	0.10	1	70%	Low-sulfur Diesel
LCV gasoline (E10)	183,363	3.5	2.59	1	54%	Ref. Gasoline (E10)
MDV - Diesel	804,670	15.0	9.07	1	30%	Low-sulfur Diesel
HCV - Diesel	1,609,340	30.0	19.04	1	5%	Low-sulfur Diesel
School bus - Diesel	400,000	11.0	0.60	54	92%	Low-sulfur Diesel
Transit bus - Diesel	400,000	15.0	2.00	50	30%	Low-sulfur Diesel
Fuel cell LDV	173,151	1.9	0.10	1	70%	Comp. gas. H2 from solar
Fuel cell LCV	183,363	3.5	2.59	1	54%	Comp. gas. H2 from solar
Fuel cell MCV	804,670	15.0	9.07	1	30%	Comp. gas. H2 from solar
Fuel cell HCV	1,609,340	30.0	17.27	1	5%	Comp. gas. H2 from solar
Fuel cell bus	400,000	11.0	0.60	54	92%	Comp. gas. H2 from solar

Table 2 refers to the assumptions made for the individual vehicle segments. For example, as the size of the vehicle increases, a higher number of kilometres driven (range from approx. 171k to 1.6 mn) is assumed for the entire life cycle. A similar approach is taken with the assumptions for the vehicle weight (range from 1.3 to 30 tonnes) and payload (range from 100 kg to 19 tonnes). The number of passengers is set as 1 in each case except for buses (50-54 passengers). Depending on the intended use of the vehicle, the percentage of kilometres driven in urban (5-92%) or rural areas (8-95%) differs. While the fuel production pathway for the gasoline vehicles was assumed to be "reformulated gasoline (E10) for blending and transport to the filling station" (Ref. Gasoline E10), the pathway for the diesel vehicles is "low sulfur diesel from crude oil". In the case of the FCEV, the pathway used in each case is "compressed gaseous hydrogen from solar energy" (Comp. gas. H_2 from solar). The latter represents a CO_2-neutral pathway.

The evaluation of the WTW/C2G analysis includes three major sets of results. The first one shows the WTP (well-to-pump) results and includes the upstream process in the fuel production and distribution. The second set, "operation only", covers all energy and emissions generated during vehicle operation and includes both combustion-related and non-combustion related (i.e. brake, tire, wear) emissions. These two blocks together yield the WTW results in the narrower sense, i.e. without taking into account the energy and emissions from the vehicle construction process. The latter, in turn, is taken into account in the third analysis set and relates to vehicle construction and among others includes subcategories such as fluids, battery, components, ADR (Assembly Disposal and Recycling), among others. To calculate the impact of these subcategories, the energy and emissions from these subgroups are related to the total lifetime mileage of the vehicle, and the energy required, and emissions generated in the upstream process to build the vehicle are also taken into account.
Adding the third set to the WTW results (summation of the first two sets) yields a WTW analysis in the broader sense, or a C2G analysis of CO_2 emissions. (GREET 2016: 17-18)

The calculation of well-to-wheel CO_2 emissions is as follows:

$$WTW_{CO_2} = WTP_{CO_2} + PTW_{CO_2} \tag{4}$$

where WTW_{CO_2} are the well-to-wheel CO_2 emissions (g/km), WTP_{CO_2} are the well-to-pump CO_2 emissions (g/km), and the PTW_{CO_2} are the CO_2 emissions from the vehicle operation (g/km)

The WTW result forms the first part of the cradle-to-grave calculation. The second part, which is kept in parentheses in the following equation for better understanding, relates to vehicle construction (incl. assembly disposing and recycling). Together, the C2G result is derived as shown in calculation 3.4:

$$C2G_{CO_2} = WTW_{CO_2} + (C_{CO_2} + ADR_{CO_2} + F_{CO_2} + B_{CO_2} + O_{CO_2}) \quad (5)$$

where $C2G_{CO_2}$ are the cradle-to-grave CO_2 emissions (g/km), WTW_{CO_2} are the well-to-wheel CO_2 emissions in g/km, C_{CO_2} are the components CO_2 emissions (vehicle body, powertrain systems, transmission system/gearbox, traction motor (BEV, FCEV), electronic controller (BEV, FCEV), fuel cell onboard storage (FCEV)) in g/km, ADR_{CO_2} are the CO_2 emissions in g/km from assembly disposal and recycling, F_{CO_2} are the fluids CO_2 emissions in g/km, B_{CO_2} are the battery CO_2 emissions in g/km and O_{CO_2} are the other CO_2 emissions (trailer chassis, trailer auxiliary, driver axel lubricant, wheel-end lubricant: drive axel) in g/km
(GREET 2016: 19; GREET® Model 2021)

The next step is to compare the CO_2 emissions determined in the GREET® model with those of the Austrian Umweltbundesamt in order to check the plausibility of the data.
Subsequently, the CO_2 emissions of the fuel cell vehicle categories (measured in g/km) determined in the GREET® model for the years 2025, 2030, 2035, 2040, 2045 and 2050 are compared with those of the same vehicle categories running with combustion engines. The difference between the CO_2 emissions of the respective vehicle segments results in the savings potential of the corresponding vehicle fleet segment (e.g., the total CO_2 emissions of the ICE-LDV fleet minus the total CO_2 emissions of the FCEV-LDV fleet). Depending on the scenario, this results in a differently scaled FCEV fleet and thus a larger or smaller different CO_2 savings potentials for the respective periods.

Finally, the demand for renewable energies required for the respective FCEV fleets is calculated for Austria. These quantities are then compared to the actual amount of electricity produced in Austria from renewable energies. The aim is to show the additional demand for renewable energy in Austria that would be created by an FCEV fleet, depending on the scenario, and whether this demand could be met.

4) Data analysis

4.1. Main fields of research

The aim of this master thesis is to evaluate the potential and limitations of green hydrogen for the decarbonisation of the Austrian transport sector. In order for green hydrogen to make a significant contribution, it is a prerequisite that an economic case can be presented within the next 10-20 years. The economic viability ultimately depends on many factors. In this work three factors have been identified as the most important.

Firstly, the costs for the production of green hydrogen must be or become competitive with other hydrogen production processes, but also with fossil fuels. Not only the investment costs in an electrolysis plant play a role, but also the electricity generation costs for renewable energies such as solar, wind and hydropower. The costs of fossil fuels, in turn, can be negatively influenced by a CO_2 tax or carbon pricing.

Secondly, decarbonisation of the transport sector through green hydrogen requires that the TCO of an FCEV is competitive with BEVs and ICEs.

The third factor concerns the policy framework for a hydrogen economy. This can contribute significantly to the economic viability of the first two factors through investment in infrastructure, incentives in the form of subsidies and/or a carbon tax or carbon pricing.

If the question of an economic case can be answered predominantly positively, as in this work, the analysis takes place with regard to the specific potential of green hydrogen and FCEVs for the decarbonisation of the Austrian transport sector. Since these are forecasts and are subject to a high degree of uncertainty due to the long forecast period until 2050, it seems reasonable to calculate several scenarios for the decarbonisation potential of green hydrogen in the Austrian transport sector.

Finally, the question still remains to what extent sufficient electricity from renewable energies can be provided in Austria for the expected additional demand for green hydrogen, depending on the scenario.

4.2 Levelised cost of Hydrogen

Currently, the levelised costs of hydrogen production in the steam reforming process using natural gas are reported in the literature to be significantly lower than in the electrolysis process for the production of green hydrogen. The IEA puts the price of the SMR process at USD 0.50-1.70/kg for 2020, compared to green hydrogen costs of USD 3.00-8.00/kg. However, it is generally expected that the cost of hydrogen production will have fallen significantly by 2030 and will already be competitive in some parts of the world. The costs for renewable energies play a major role in this. Depending on the electricity price and full load hours, these can account for up to 50-90% of the total costs. (IEA 2021a: 113) NEL puts the share of renewable energies at around two-thirds based on an electricity price of USD 20 MWh. (expert interview with NEL, December 2021) Clearly, however, this percentage is a changing variable, as the electricity costs for renewable energies are subject to constant change. Especially in the case of surplus electricity from renewables, electricity prices could be very cheap, making the cost of green hydrogen production competitive, at least temporarily. However, in the case of larger, continuous demand, this option seems not to be sufficient. (Shell 2017: 15, 18)

The cost of producing electricity using wind or solar has fallen massively in recent years. Overall, the levelised cost of electricity for solar PV has fallen by 85% in the period 2010-2020. In the Middle East and Portugal, auctions have already been finalised at just under EUR 12/MWh. (at an EUR/USD exchange rate of 1,137; Reuters 2020: online) This also fits with a statement by Raymond Carlsen, CEO of the Norwegian energy company Scatec, - a company that is currently building a 100 MW green hydrogen facility with PEM technology in Egypt - according to which the cost of electricity for solar power in Egypt or Tunisia is as low as USD 25/MWh. (expert interview with Scatec ASA, January 2022; Bloomberg transcript of the Q3 2021 earnings call, October 2021) In the case of onshore wind and offshore wind, the cost reduction for the period 2010-2020 is 56% and 48% respectively. (IRENA 2021: 11) In the medium to long term, the learning curve also suggests that the LCOE will continue to fall. The learning curve or learning rate describes "the fractional reduction in cost for each doubling of cumulative production or capacity" (Rubin et al. 2015: 1)

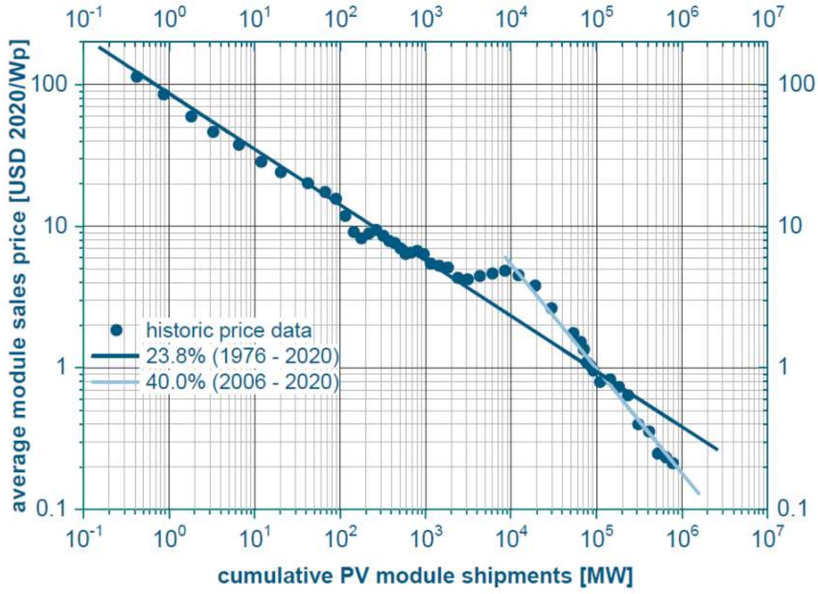

Figure 12: Learning curve PV module systems (ITRPV 2021: 62)

Figure 12 demonstrates the learning curve in logarithmic scale. The y-axis shows how much the average module sales prices fall for each doubling of the cumulative capacities (x-axis). The straight lines represent the learning rate, the dots the price data for the individual years. In the period 1976-2020 cost reductions of 23.8% were achieved with each doubling of cumulative capacity. From 2006-2020, this was as high as 40.0%. (VDMA 2021: 63)

In the case of onshore wind, the learning rates are lower since this technology is already more mature. Rubin et al. have found a range of -11% to 35% when reviewing numerous studies. The average learning rate is 12%. (Rubin et al. 2015: 8) In its World Energy Outlook 2021, the IEA forecasts in its "Stated Policies Scenario" that solar PV capacity will increase 3.5-fold by 2030 compared to 2020, or more than 8-fold by 2050. Assuming a learning rate of 23.8%, electricity production costs from solar PV would drop 49% by 2030 and 87% by 2050. For wind, the projections call for an increase of more than double by 2030 and 4-fold by 2050. Assuming a 12% learning rate, wind electricity production costs would thus fall by just over 12% by 2030 and 40% by 2050. In their "Net Zero Emissions by 2050 Scenario", solar PV capacity growth is just under 7-fold by 2030 and nearly 20-fold by 2050. In the case of wind, the projections call for an increase of just over 4-fold by 2030 and 11-fold by 2050. (IEA 2021b: 297, 312) In this scenario, the fallback in electricity production costs would be thus correspondingly larger.

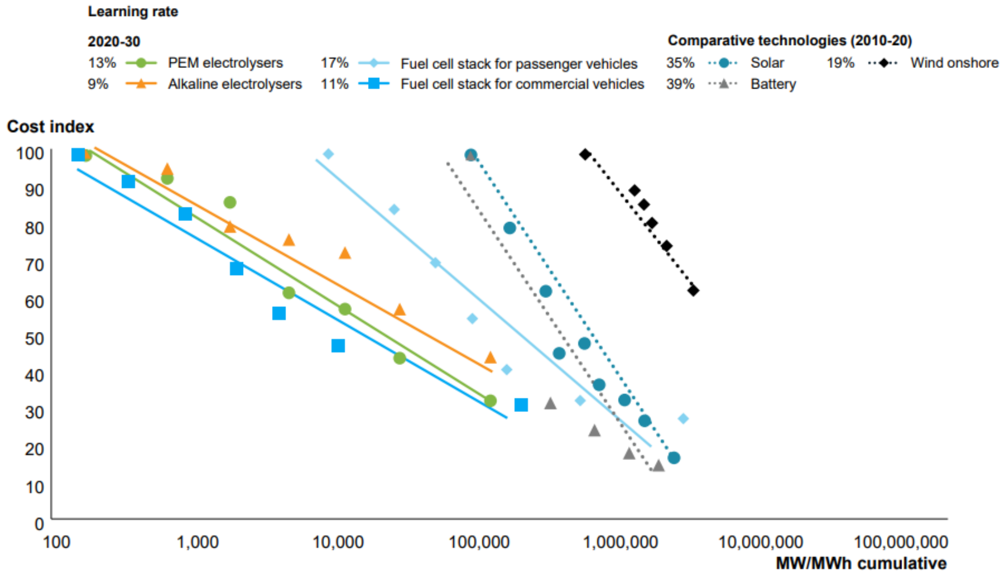

Figure 13: Capex development of selected technologies over total cumulative production (Hydrogen Council 2020: 13)

As can be seen in Figure 13, learning rates in the hydrogen space will be lower in the 2020-2030 period than those for solar, battery, or wind have been in the last decade. The Hydrogen Council predicts that the cost of PEM electrolysers will fall by 13%, and that of alkaline electrolysers by 9%. If these assumptions are combined with those of the IEA regarding the cumulative electrolysis capacities from 2020 to 2030 - these see a growth from currently 290 MW to 54 GW by a factor of 7.5 (see chapter 2), the costs for PEM electrolysis would fall by 65%, those for alkaline electrolysis by approximately 51% in this time period. (Hydrogen Council 2020:13; IEA 2021a: 117)

Bristowe and Smallbone conclude in their study that the $LCOH_2$ could fall from USD 4.16/kg in 2020 to USD 2.63/kg with a tenfold increase in capacity, or to USD 1.57/kg with a hundredfold increase in capacity (range of USD 0.95/kg to USD 2.22/kg). The electricity feed stock is based on offshore wind. Its share of the USD

1.53/kg cost reduction in the event of a tenfold increase in capacity amounts to USD 1.00/kg. (Bristowe et al: 16, 17)

This is in line with an analysis by financial services firm BloombergNEF that $LCOH_2$ from renewables for projects financed in the second half of 2021 are less than USD4/kg in some parts of the world. (BloombergNEF 2021a: 6) Most of the electricity comes from offshore wind. In Brazil, the costs are already just under USD 2/kg in the best case, and the technology used is alkaline electrolysers.

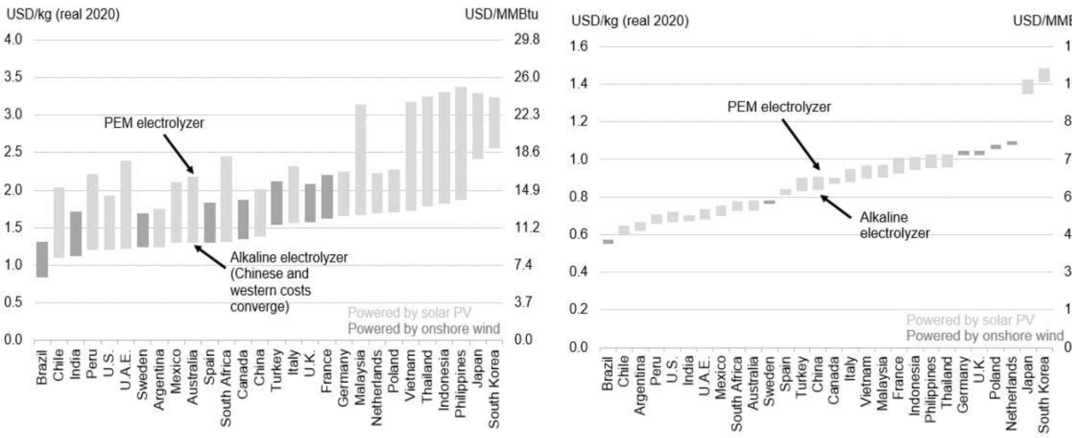

Figure 14 and 15: Renewable $LCOH_2$, 2030 (left graph) and 2050 (right graph) (Bloomberg 2021a: 7, 8)

As can be seen in Figure 14, $LCOH_2$ is expected to fall to less than 2 USD/kg in many countries by 2030. Depending on the country, this cost structure will then be achieved either with electricity from photovoltaics or wind power; alkaline electrolysers will still achieve the lower costs than PEM technology. (BloombergNEF 2021a: 7)

Figure 15 shows that in 2050, the cost of producing H_2 from renewables will be less than $1/kg in most countries. PV is the dominant energy source for H_2 production at this time. From a technological point of view, there is a strong convergence of costs for production using alkaline electrolysers and PEM electrolysers. (BloombergNEF 2021a: 8)

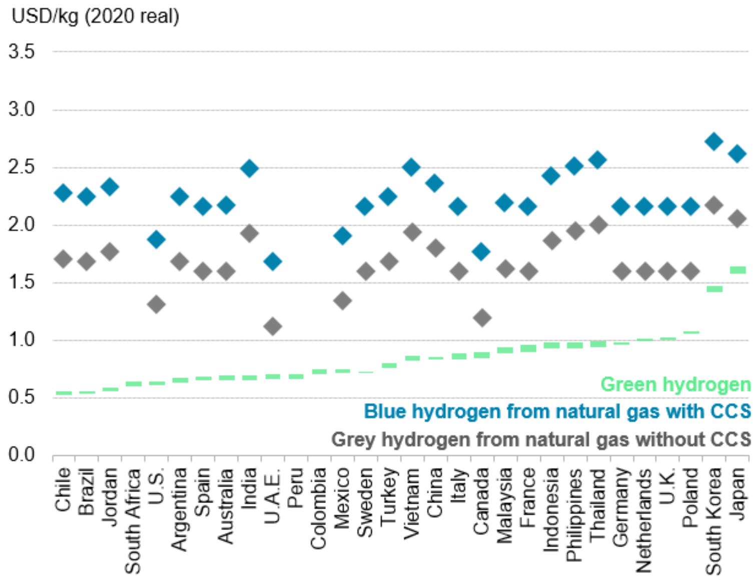

Figure 16: $LCOH_2$ of green, blue and grey hydrogen in 2050 (BloombergNEF 2021a: 14)

Figure 16 shows the results of an analysis by BloombergNEF of the $LCOH_2$ in 30 countries based on future projects. According to this analysis, the cost of producing green hydrogen in 2050 is expected to be lower than that of blue or grey hydrogen in all countries. In the best case - in the case of Chile - $LCOH_2$ based on tracking PV is projected to fall to USD 0.53/kg. In 2030, green hydrogen should at least be cheaper than blue hydrogen in a majority of countries, but compared to grey hydrogen, the results show that this would only be the case in selected countries such as Brazil or Chile. (BloombergNEF 2021a: 14)

The approximate costs for green hydrogen in Austria can best be derived from the costs in Germany. Here, the $LCOH_2$ for 2030 is estimated at 1.6 USD/kg for alkaline electrolysers and 2.16 USD/kg for PEM electrolysers. (BloombergNEF 2021a: 7)

Table 3: $LCOH_2$ for renewable hydrogen (Fuel Cell and Hydrogen Observatory 2021: online)

	PV			Onshore wind		
	avg	top	max	avg	top	max
Capacity factor	12.7%	14.5%	15.9%	22.0%	34.0%	39.0%
$LCOH_2$ (EUR/kg)	**5.81**	**5.08**	**4.65**	**6.14**	**4.09**	**3.60**

Table 3 provides specific data for the theoretical $LCOH_2$ in Austria for the year 2021. Theoretical because the production costs for water electrolysis are not based on plants currently in operation, but on the current costs for a state-of-the-art multi-MW electrolysis system with a lifetime of 30 years. Here, the Fuel Cell & Hydrogen Observatory (an initiative of the Fuel Cells and Hydrogen Joint Undertaking) calculates the cost of green hydrogen directly coupled to energy sources such as PV or onshore wind for Austria in 2021. If onshore wind is the energy source, the costs are EUR 3.6/kg (USD 4.1/kg at a EUR/USD exchange rate of 1.1326, ECB 2022: 1) in the most favorable wind case, EUR 4.1/kg (USD 4.6/kg) in the top 10-15% of locations and about EUR 6/kg (USD 7.0/kg) on average. If PV serves as the energy source, the average $LCOH_2$ is EUR 5.8/kg (USD 6.6/kg), in the most favorable case it is EUR 4.7/kg (USD 5.3/kg) and EUR 5.1/kg (USD 5.8/kg) in the top 10-15% of locations. Production costs of April 2021 were taken as the cost basis for PV and wind. The costs are significantly influenced by the capacity factor, which for PV is 12.7% on average or 15.9% in the best case, and for onshore wind is 22% on average or 34% in the most favourable environment. This factor is calculated by dividing the actual annual amount of electricity produced by a plant by the annual amount of electricity produced by a plant of the same size, assuming that the latter produces at full load all year. (Piasecki et al. 2019: 4)

The energy efficiency of a state-of-the-art multi-MW plants is around 70% for alkaline electrolysis and around 77% for PEM electrolysis. (IEA 2019a: 44; expert interview with ITM Power, December 2021) For an alkaline system CAPEX of EUR 600/kW_e are assumed, for a PEM system of EUR 900/kW_e. In addition, 20% of the CAPEX for stack replacement costs as well as 4% and 2% of the CAPEX for alkaline and PEM in the form of other OPEX are assumed. (FCHO 2021: online)

Under the assumptions of the learning rates for wind, solar PV and electrolysis described above and the significant expansion of capacities for solar PV, wind, and electrolysis until 2030 as predicted by the IEA, it seems quite realistic that the $LCOH_2$ will drop by more than 50% until 2030. From 2030 to 2050, it should be possible to reduce costs again by at least 50% based on the projected capacities. Taking the previously mentioned costs of EUR 6/kg for the year 2021 as a basis, $LCOH_2$ of less than EUR 1.5/kg could be reached by 2050.

As a consequence, it shows that from today's perspective, the costs for $LCOH_2$ should be competitive in ten years, at least compared to "blue" hydrogen. (Bloomberg 2021: 13, 14) When comparing with "grey" hydrogen it is of crucial importance where the price of CO_2 is developing towards. The faster and more clearly it rises, the sooner green hydrogen can be considered competitive.

4.3 Total cost of ownership

The TCO method is widely used in the literature, but also by companies, in order to compare different vehicle technologies as comprehensively and transparently as possible in terms of their economic efficiency. (Liu et al. 2021: 1) Therefore, a TCO approach is used in this master thesis to compare different vehicle technologies - despite the fact that the purchase decision in the passenger car segment is not based on purely rational considerations as elaborated in chapter two.

In the following, the current and future costs of ICEs, BEVs and FCEVs for all four vehicle segments (LDV, LCV, MCV & HCV, bus) are compared using the TCO approach. In addition to the comparison of these three different vehicle technologies, the focus is placed specifically on the future cost development of FCEVs.

The costs of an FCEV differ primarily from those of an ICE or a BEV in terms of the fuel cell system and storage system. If one takes the Toyota Mirai (128 kW_e) as an example, the costs for the fuel cell system (FC stack, balance of plant) and the fuel cell storage costs amount to more than 50% of the overall production costs. Assuming an annual production of 3,000 units, this resulted in fuel cell system costs of USD 165/kW_e in a study conducted by Strategic Analysis. (Strategic Analysis 2018: 96; Toyota 2022: 15) This, in turn, corresponds fairly closely with the 171/kW$_e$ assumed by BloombergNEF for a light duty vehicle with 100 kW$_e$ for the year 2020. (BloombergNEF 2020: 15) According to the U.S. Department of Energy (DOE), the costs for LDV fuel cell systems (80 kW$_e$) have fallen by 70% since 2008. (U.S. Department of Energy 2021: 8)

With significantly higher production figures and an assumed learning curve of 22%, costs can be expected to fall significantly in the coming years and decades. (BloombergNEF 2020: 14) DOE calculates that at a production of 100,000 units per year, todays costs would be USD 76/kW$_e$, more than 50% below current costs. The DOE targets for 2025 envisage a further halving of costs to USD 40/kW and a final target of USD 30/kW$_e$. (U.S. Department of Energy 2021: 8)

In the following, the TCO for a FCEV, BEV, and ICE of the four vehicle segments (LDV, LCV, MCV & HCV and bus) are presented for the year 2030.

Table 4: TCO assumptions for the four vehicle segments (LDV, LCV, truck, and bus) for 2030 in Europe (own compilation based on several sources[1])

TCO assumptions 2030	Light-duty vehicle (LDV)			Light commercial vehicle (LCV)		
	FCEV	BEV	ICE Gasoline	FCEV	BEV	ICE Gasoline
Initial purchase price (EUR)	43,358	31,569	28,219	51,855	34,953	34,906
Fuel price FCEV (EUR/kg H_2) **Fuel economy FCEV** (km/kgH_2)	3.5 191.39			3.5 150.38		
Fuel price BEV (EUR/kWh) **Fuel economy BEV** (km/kWh)		0.09 7.48			0.09 8.21	
Fuel price ICE (EUR/litre) **Fuel economy ICE** (km/litre)			1.48 24.39			1.48 21.72
Maintenance costs (EUR/km)	0.07	0.06	0.05	0.06	0.06	0.05
Insurance costs per year (EUR)	402	305	366	402	369	436
Vehicle kilometres per year (km)	15,000			15,000		
Lifetime (years)	10			10		
Residual value	10%			10%		
Discount rate	10%			10%		
Consumer Price Index	1.5%			1.5%		

TCO assumptions 2030	Heavy-duty truck			Bus		
	FCEV	BEV	ICE Diesel	FCEV	BEV	ICE Diesel
Initial purchase price (EUR)	141,453	260,071	89,500	287,339	268,233	292,471
Fuel price FCEV (EUR/kg H_2) **Fuel economy FCEV** (km/kgH_2)	3.5 13.16			3.5 15.04		
Fuel price BEV (EUR/kWh) **Fuel economy BEV** (km/kWh)		0.09 0.79			0.09 0.71	
Fuel price ICE (EUR/litre) **Fuel economy ICE** (km/litre)			1.41 3.28			1.41 2.78
Maintenance costs (EUR/km)	0.11	0.10	0.12	0.16	0.16	0.18
Insurance costs per year (EUR)	849	1,560	537	3,085	2,212	3,450
Vehicle kilometres per year (km)	140,000			40,000		
Lifetime (years)	10			10		
Residual value	10%			10%		
Discount rate	10%			10%		
Consumer Price Index	1.5%			1.5%		

[1] Fuel Cells and Hydrogen 2 Joint Undertaking 2021: 327-329, 332, 343, 345, 347; Deloitte 2020: 44, 45; Hyundai 2021: online; Liu et al. 2018: 8; BloombergNEF 2020: 23, 24; ADAC 2022: online; ÖAMTC 2022: online; Wien Energie 2022: online; Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie 2021c: online; IEA 2019b: 11; Toyota 2021: online

Table 4 lists all assumptions for the year 2030 that are included in the TCO calculation of the individual vehicle technologies (FCEV, BEV, ICE) from the four vehicle segments. Assumptions were also made for the current TCO of the individual vehicle technologies from the analysed vehicle segments; these are listed in the appendix. All assumptions refer to the European market.

In the LDV and LCV segments, the costs of purchasing a fuel cell electric vehicle in 2030 are significantly higher than those of a BEV and ICE (range from 37% to 54%). Nevertheless, a comparison of the expected sales price in 2030 with current sales prices reveals a decrease for fuel cell electric vehicles of -27% for LDVs and -33% for LCVs, which is about twice as high as for the two BEV vehicle segments. In contrast, the ICE counterparts show a slight sales price increase until 2030. (ADAC 2022: online; BloombergNEF 2020: 23) The picture is completely different for trucks. In 2030, the BEV truck is the most expensive vehicle from today's perspective due to the high battery costs. The costs for the fuel cell electric truck will roughly halve by 2030 (compared to today), while those for a BEV truck will fall by around 1/3 and those for the diesel truck will show a slight increase. (Fuel Cells and Hydrogen 2 Joint Undertaking 2021: 327-329, 332, 343) For buses, the picture is much more homogeneous, whereby the assumption for the diesel bus result in a slightly higher sales price than for a BEV bus or fuel cell bus. Here, too, the costs for the fuel cell bus are expected to be halved, the costs for a battery electric bus fall by more than 30%, and those for a diesel bus rise by around 3%. (Deloitte 2020: 44)

The fuel prices underlying the calculations in turn play an important role in this TCO calculation. Here, the price of a kilo of hydrogen was assumed to be EUR 3.5/kg (minus 50% compared to today), an assumption that, as explained in Chapter 4.2, does not appear to be too optimistic in any case. The same applies to the projected electricity price of 9 euro cents per kWh, which corresponds to a minus of 57% compared to today. (BloombergNEF 2020: 23; Wien Energie 2022: online; ÖAMTC 2022: online) A value of 1.48 EUR/litre is assumed for the gasoline price. This is calculated from the average gasoline price paid at Austrian gas pumps in 2021, adjusted for inflation of 1.5% per annum (p.a.). (ÖAMTC 2021: 1) This assumption might turn out to be too low against the background of a possible higher carbon tax/pricing.

Fuel economy also has a quite significant impact on TCO. The more efficient the vehicles are, the more advantageous the impact on the TCO calculation. In the case of fuel cell LDVs, an improvement of around 60% compared to today to more than 190 km/kgH_2 is assumed by 2030, which means that in 2030 it should be possible to cover almost 1,000 km with a 5-kg tank. (Toyota 2021: online) While the estimated improvement for a fuel cell LCV is still around 50%, the assumptions for a fuel cell truck at around 12% and a fuel cell bus at a good 20% are significantly less optimistic. (Liu et al. 2018: 8; Fuel Cells and Hydrogen 2 Joint Undertaking 2021: 347) The fuel economy for BEVs shows relatively small improvements between today and 2030, ranging from 7% for LDVs to 22% for buses. (ADAC 2022: online; BloombergNEF 2020: 24) The outlook for the fuel economy for ICEs is much more optimistic for LDVs and LCVs with an improvement of almost 40%. The latter assumptions are based on the European Commission's paper "CO_2 Standards for New Cars and Vans" and is based on the requirements for achieving the fleet limit of 95 g/km (equivalent to 4.1 litres per kilometre for gasoline and 3.6 litres per kilometre for diesel), which has been in force since 2020. (European Commission 2019: 3) For maintenance costs, the cost differences between the individual technologies are relatively small, with battery-powered vehicles tending to have slightly lower absolute costs. For 2030, maintenance costs for both FCEVs and BEVs are expected to decrease by almost 10% by 2030. (IEA 2019b: 11; ADAC 2022: online) Insurance costs for LDVs and LCVs are based on current data from ÖAMTC and are expected to increase by an inflation rate of 1.5% p.a. until 2030. The insurance costs for trucks are estimated at 0.6% of the initial purchase price. (Fuel Cells and Hydrogen 2 Joint Undertaking 2021: 347) In absolute terms, the costs are highest for buses, but as a result of the significant drop in the purchase price of a fuel cell bus, insurance costs are also expected to halve. (Deloitte 2020: 45) The annual vehicle kilometres for LDVs and LCVS in the TCO calculations amount to 15,000 km each, those for trucks 140,000 km and those for buses 40,000 km. (ADAC 2022: online; Fuel Cells and Hydrogen 2 Joint Undertaking 2021: 345; GREET model 2021)

Subsidies are also taken into account in the calculations and are deducted directly from the initial purchase price of the affected vehicles. In Austria, the purchase of both an FCEV and a BEV will be subsidised by 5,000 euros in 2022. (Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie 2021c) However, the price of an LDV or LCV may not exceed EUR 65,000. (Kommunal Kredit Public Consulting 2021: online) Thus, from today's perspective, in the FCEV space for 2022, only the Toyota Mirai with a base price of just over EUR 60,000 is eligible, while Hyundai's Nexo model is currently offered with a base price of over EUR 77,000. (ADAC 2022: online) The situation is similar with the Austrian Normverbrauchsabgabe (NOVA). This leads to a higher initial purchase price for LDVs and LCVs powered by diesel or gasoline and is calculated using the Nova calculator of the Federal Ministry of Finance. (Bundesministerium für Finanzen 2022: online) In the case of FCEVs or BEVs, the purchaser of a vehicle is currently exempt from NOVA under the Normverbrauchsabgabegesetz (§ 3. Abs. 1 Z 1 NoVAG 1991), as these have a CO_2 emission value of 0 g/km at the point of use. (Rechtsinformationssystem des Bundes (RIS) der Republik Österreich 2022: 3)

Table 5: TCO results for the vehicle technologies (FCEV, BEV, ICE) of the four vehicle segments (LDV, LCV, truck and bus) for 2030 and today in Europe (own calculations)

TCO (EUR/km)		Light-duty vehicle (LDV)			Light commercial vehicle (LCV)		
		FCEV	BEV	ICE Gasoline	FCEV	BEV	ICE Gasoline
today	Capex	0.38	0.23	0.18	0.50	0.26	0.22
	Fuel	0.04	0.02	0.05	0.05	0.02	0.05
	O&M	0.07	0.06	0.07	0.06	0.06	0.08
	Total TCO	**0.48**	**0.31**	**0.30**	**0.60**	**0.34**	**0.36**
2030	Capex	0.28	0.20	0.18	0.33	0.22	0.22
	Fuel	0.01	0.01	0.04	0.02	0.01	0.04
	O&M	0.06	0.05	0.05	0.06	0.06	0.05
	Total TCO	**0.35**	**0.26**	**0.27**	**0.40**	**0.29**	**0.32**

TCO (EUR/km)		Heavy-duty truck			Bus		
		FCEV	BEV	ICE Diesel	FCEV	BEV	ICE Diesel
today	Capex	0.21	0.27	0.06	1.52	0.96	0.68
	Fuel	0.39	0.18	0.27	0.35	0.18	0.32
	O&M	0.09	0.08	0.09	0.22	0.19	0.19
	Total TCO	**0.69**	**0.53**	**0.42**	**2.09**	**1.33**	**1.19**
2030	Capex	0.10	0.18	0.06	0.69	0.64	0.70
	Fuel	0.18	0.07	0.28	0.15	0.08	0.33
	O&M	0.08	0.07	0.08	0.16	0.14	0.18
	Total TCO	**0.35**	**0.33**	**0.43**	**1.00**	**0.87**	**1.21**

Table 5 shows the results of the TCO calculations for 2030 and for today for the vehicle technologies (FCEV, BEV, ICE) of the four vehicle segments (LDV, LCV, truck, and bus). The individual TCO calculations are provided in the appendix.

Within the LDV segment, TCO for BEV and ICE vehicle (gasoline) are very close to each other both today and in 2030, with minimal advantages for BEV in 2030. The FCEV is still over 30% more expensive in 2030. In the TCO calculation, the part relating to the purchase price of a FCEV already makes this vehicle more expensive than the total TCO of a BEV and an internal combustion vehicle. Nevertheless, the TCO for the FCEV in 2030 show by far the strongest decline, with a drop of around 27% compared to today.

The picture is similar for LCVs. Once again, the BEV is just ahead of the ICE vehicle. Due to the high initial purchasing price, the FCEV has higher TCO of around 78% compared to the BEV and just under 70% compared to the ICE vehicle. The fact that the TCO can be reduced twice as much in 2030 as with a BEV compared to today has only an insufficient effect.

From a fuel cell perspective, the other two vehicle segments, heavy-duty trucks and buses, are far more interesting. Compared to an FCEV, the TCO for trucks in 2030 is only 2 cents lower for the BEV, while it is already 22% higher for the diesel truck. Here, the high fuel costs of 28 euro cents/km compared to the fuel cell truck of 0.18 euro cents/km have the greatest negative impact. Overall, the TCO for a fuel cell truck drop by almost 50%.

In the bus segment, the BEV again performs best in 2030. It has about 13% lower TCO than a fuel cell bus, while the latter in turn has about 18% lower costs than a diesel-powered bus. Again, the FCEV shows by far the largest percentage decrease compared to current costs (-55%).

The analysis of the TCO results shows that the fuel cell, due to being the least mature technology, can achieve by far the largest cost reductions. In addition, it also indicates that the pendulum could swing in favour of FCEVs by 2030 at the latest, especially for the heavier commercial vehicles compared to ICEs. These results are in line with statements made by Daimler Truck at its Strategy Day in May 2021, according to which BEV trucks could reach TCO parity (with a diesel truck) after 2025 and FCEV trucks after 2027. (Daimler Truck 2021: 40)

However, especially in comparison with the ICE vehicles it becomes obvious that the fuel price for gasoline and diesel is a significant determinant of the TCO calculation and that these calculations are therefore subject to a not insignificant degree of uncertainty. If one considers the fluctuations in fuel prices and electricity prices in the period from 2008 to 2015, it becomes clear that the total TCO may well change significantly until 2030. (Ecofys 2016: 2, 3, 6)
Furthermore, the results of these TCO calculations fit well with the two BloombergNEF scenarios mentioned earlier, where the share of FCEVS increases more the heavier the vehicles are. BloombergNEF calculates in its strong policy scenario that by 2050, FCEV market share would range from 10% for LDVs to 50% for heavy duty vehicles, depending on the vehicle type. This policy implies new sales for all vehicle segments to exceed 1.3 mn FCEVs and the total fleet to exceed 3.5 mn FCEVs by 2030. This compares to a total fleet (ICE, BEV, FCEV) of 1.7 bn vehicles at this point in time. To achieve this, approaches like the one in Japan regarding hydrogen refuelling stations or the EU's 2030 emission standards are needed. Overall, USD 105 bn (EUR 92.3 bn at an EUR/USD exchange rate of 1.137) in subsidies for infrastructure and FCEVs will be needed between 2020 and 2030, 57% of which go to FCEVs. (BloombergNEF 2020: 2) In a separate "2050 decarbonisation scenario" (zero tail pipe emissions based on usage of battery electric as well as fuel cell drivetrains), these FCEV shares would range between 25% for light duty vehicles and 75% for heavy duty commercial vehicles. (Bloomberg 2020: 21) The latter scenario is also the basis for the "decarbonisation scenario" of this master thesis. More details on this scenario are provided in chapter 3.

As previously mentioned, the likelihood of a possible further significant increase in CO_2 prices should not be underestimated. In its report "Net Zero by 2050 - A Roadmap for the Global Energy Sector", the IEA expects a CO_2 price of USD 130/tonne (EUR 115/tonne at an EUR/USD exchange rate of 1.1326, ECB 2022: 1) in 2030, followed by an increase to USD 205/tonne (EUR 181/tonne) in 2040 and USD 250/tonne in 2050 (EUR 221/tonne). (IEA 2021c: 52) These forecasts seem quite realistic in view of a CO_2 price that was quoted at almost EUR 90/tonne already in December 2021. (S&P Global: 2022: online)

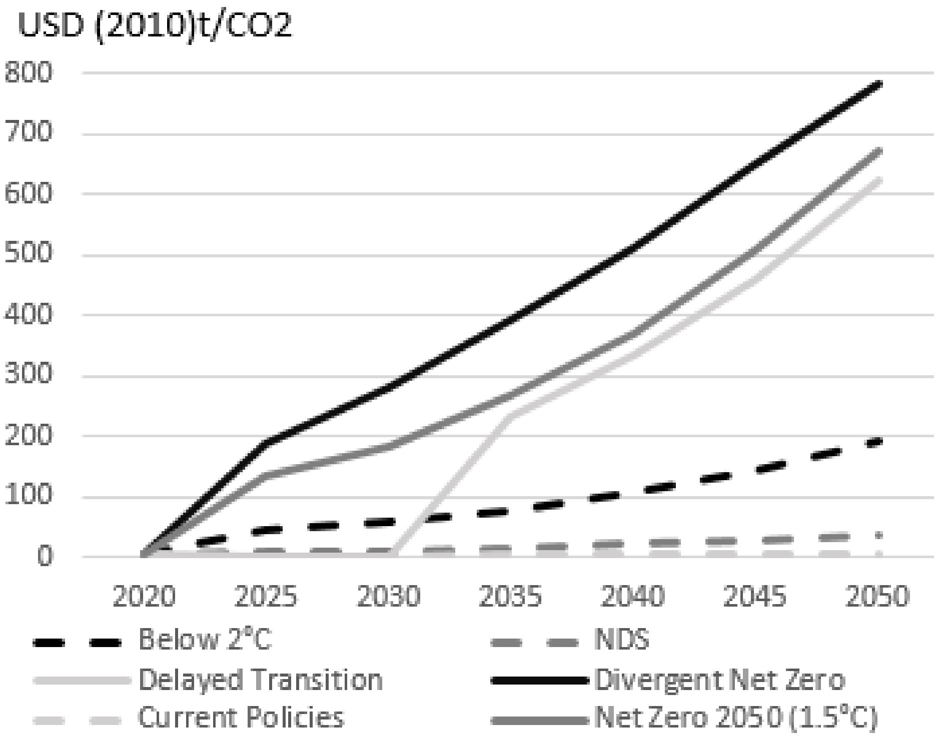

Figure 17: Carbon price development (NGFS 2021: 8)

Figure 17 plots expected CO_2 price trends under six different scenarios published by The Network of Central Banks and Supervisors for Greening the Financial System (NGFS). In three of its six scenarios the CO_2 price will rise to more than USD 600/tonne (EUR 530/tonne) by 2050. (Network for Greening the Financial System 2021: 15)

Table 6 shows the impact of a CO_2 price of USD 130/tonne (EUR 114.8/tonne) and USD 700/tonne (EUR 618.0/tonne) on the TCO for a LDV with combustion engine, using the example of the fleet limit of 95 g/km (equivalent to 4.1 litres per kilometre for gasoline and 3.6 litres per kilometre for diesel), which has been in force since 2020. (European Commission 2019: 3)

Table 6: CO_2 impact on TCO under different CO_2 price assumptions for an LDV and LCV with internal combustion engine (own calculations)

CO_2 price - USD per ton	130.0	700.0
CO_2 price - EUR per ton (EUR/USD=1,137)	114.8	618.0
emitted CO_2 in kg per gallon of diesel	10.19	
emitted CO_2 in kg per gallon of gasoline	8.50	
emitted CO_2 in kg per litre of diesel	2.69	
emitted CO_2 in kg per litre of gasoline	2.25	
CO_2 price per litre of diesel (EUR)	0.31	1.66
CO_2 price per litre of gasoline (EUR)	0.26	1.39
CO_2 price per km of diesel (euro cent) - net	1.11	5.99
CO_2 price per km of gasoline (euro cent) - net	1.06	5.69
CO_2 price per km of diesel (euro cent) - gross	**1.33**	**7.19**
CO_2 price per km of gasoline (euro cent) - gross	**1.27**	**6.83**

The results in Table 6 illustrate that at a CO_2 price of USD 130/tonne (EUR 114.3/tonne), the TCO for both diesel and gasoline LDVs would be approximately 1.3 euro cents higher per kilometre. While this would not be sufficient to reduce the TCO of LDVs (and LCVs) to the necessary extent, the situation could be different in the "Net Zero 2050 (1.5°C)" scenario of NGFS. In this scenario, the CO_2 price rises to more than USD 670/tonne (EUR 594/tonne) by 2050. The resulting impact of around 7 euro cents/km would be almost sufficient to create TCO parity between a fuel cell LDV (TCO of 35 euro cents/km) and an ICE vehicle (0.27 euro cents/km) or a fuel cell LCV (TCO of 40 euro cents/km) and a gasoline-powered ICE vehicle (0.32 euro cents/km). With a realistically often higher fuel consumption per kilometre of an ICE LDV than assumed in this example, the fuel cell LDV would be ahead on a TCO basis.

The cost difference to a BEV that gets 100% of its electricity from renewable energy or (nuclear) power would of course remain unchanged. Therefore, TCO of a BEV would remain to be around 25% cheaper in the case of LDV and 29% in the case of LCV in 2030. An important factor of the higher costs of FCEVs compared to BEVs is the higher production costs of the vehicle itself. If the gap closes here, e.g. thanks to economies of scale, then the cost difference per kilometre driven would be significantly lower and many a consumer could decide in favour of the

FCEV and against a BEV due to the higher comfort, shorter charging times and a higher range. (Shell 2017: 50) If this does not happen, the BEV has little to fear in terms of competition from FCEVs in the LDV and LCV segments.

4.4 FCEV fleet - scenarios

The vehicle kilometres driven on Austrian roads over the year for the individual vehicle categories (LDVs, LCVs, MCVs, HCVs and buses) serve as the basis for calculating the CO_2 savings potential for the period 2019-2050. For this purpose, as shown in Table 7, data from the Austrian Umweltbundesamt on the vehicle fleet of the individual vehicle categories are used. (Austrian Umweltbundesamt: Results of the Austrian Air Pollutant Inventory 2021)

Table 7: Austrian annual road kilometres (Austrian Umweltbundesamt: Results of the Austrian Air Pollutant Inventory 2021)

Austrian road kilometres by vehicle segment (million)	2019	2030	2035	2040	2045	2050
LDV - Otto	22,701	26,208	26,535	26,208	25,657	24,932
LDV - Diesel	48,818	44,501	40,132	35,808	32,160	28,923
LDV - BEV	441	8,728	16,170	24,213	31,805	39,176
LDV total	**71,960**	**79,437**	**82,836**	**86,229**	**89,622**	**93,031**
LCV - ICE	7,739	8,037	7,925	7,769	7,638	7,514
LCV - BEV	46	439	836	1,284	1,726	2,178
LCV total	**7,785**	**8,476**	**8,762**	**9,053**	**9,364**	**9,691**
MCV & HCV - ICE	5,172	5,980	6,224	6,471	6,639	6,810
MCV & HCV total	**5,172**	**5,980**	**6,224**	**6,471**	**6,639**	**6,810**
Bus - ICE	532	549	554	556	554	546
Bus - BEV	3	6	8	12	18	27
Bus total	**535**	**555**	**562**	**568**	**572**	**573**

Austrian road kilometres by vehicle segment (million)	2019	2030	2035	2040	2045	2050
LDV	71,960	79,437	82,836	86,229	89,622	93,031
LCV	7,785	8,476	8,762	9,053	9,364	9,691
MCV & HCV	5,172	5,980	6,224	6,471	6,639	6,810
Bus	535	555	562	568	572	573

As shown in Table 7, total annual vehicle kilometres traveled will increase for all vehicle categories from 2019 to 2050. With the exception of the truck segment (MCV & HCV), annual kilometres driven will decrease over time for all fossil fuel-based vehicle types. For LDV-Diesel, this is expected to be the case in the near-term, for LCV-ICE from 2030 onwards, LDV-Otto from 2035 onwards and for the bus segment from 2040 onwards. In contrast, the share of BEVs in LDV, LCV and bus segments will rise steadily. Hydrogen cars do not play a role in this breakdown. However, the goal of this master thesis is nothing less than to determine the potential of hydrogen cars in relation to the entire vehicle fleet, and then to determine the potential CO_2 savings from substituting ICEs with FCEVs as well as to calculate the resulting additional demand for green electricity.

The contribution that hydrogen could make to railways, shipping, and aviation, on the other hand, is not the subject of this master thesis, given the low share of only 1.25% of total greenhouse gas emissions in the Austrian transport sector. (Austrian Umweltbundesamt 2021: 122, 124)

In the case of passenger transport, moreover, mopeds and motorcycles are not taken into account, as they only contribute just under 0.8% of total CO_2 emissions in the transport sector. With around 14.7 mn t CO_{2eq}, passenger transport had a share of 62.3% in 2019, while freight transport (heavy and light commercial vehicles) accounted for around 37.0% of CO_2 emissions. (Austrian Umweltbundesamt 2021: 124, 128)

Furthermore, it is important to mention that these calculations only deal with green hydrogen (water splitting with electrolysers from renewable energies), as grey hydrogen does not bring any appreciable improvement in the greenhouse gas balance, if at all, and blue hydrogen (hydrogen production by means of natural gas steam reforming and storage of the CO_2 under the earth's surface) is currently prohibited in Austria (even if the legal situation may of course change in the future). Furthermore, blue hydrogen is not emission-free. As much as almost 50% of the CO_2 may remain uncaptured even under optimal conditions. (Howarth et al. 2021: 2, 5)

The potential of hydrogen in Austrian transport is calculated on the basis of 3 scenarios. These are presented on the following Tables 8-10.

Table 8: FCEV share of different vehicle fleet segments in the "base scenario" (BloombergNEF 2021b)

2050 base scenario - fuel cell fleet	2019	2030	2035	2040	2045	2050
Light-duty vevicle (LDV)	0.0%	0.0%	0.1%	0.6%	1.4%	2.0%
Light commercial vehicle (LCV)	0.1%	0.1%	0.2%	0.5%	1.0%	1.6%
Medium & heavy commercial vehicle (MCV & HCV)	0.0%	0.0%	0.3%	0.9%	1.6%	2.2%
Bus	0.1%	1.0%	2.2%	3.1%	4.3%	5.7%

Table 8 summarizes the assumptions of the first scenario and is regarded as the "base scenario". This is based on the Economic Transition Scenario (ETS) from BloombergNEF. In this scenario, it is assumed that there are no new political measures that contribute significantly to achieving the Paris climate targets. Instead, developments from 2025 onwards are determined by techno-economic trends and market forces. (BloombergNEF 2021b: 17) Depending on the vehicle segment, the share of the FCEV fleet in 2050 is between 1.6% and 5.7%.

Table 9: FCEV share of different vehicle fleet segments in the "ambitious scenario" (own compilation based on several sources[2])

2050 ambitious scenario - fuel cell fleet	2019	2030	2035	2040	2045	2050
Light-duty vevicle (LDV)	0.0%	1.4%	3.6%	6.5%	9.9%	14.6%
Light commercial vehicle (LCV)	0.1%	1.6%	4.2%	7.6%	12.2%	19.3%
Medium & heavy commercial vehicle (MCV & HCV)	0.0%	0.4%	1.3%	4.1%	9.9%	18.4%
Bus	0.1%	1.4%	6.7%	11.5%	18.6%	30.2%

The second scenario, outlined in Table 9, is based on assumptions made by the Fuel Cells and Hydrogen 2 Joint Council for their "ambitious scenario". This scenario refers to Europe, in which the EU implements the measures necessary to achieve the 2°C target through coordinated efforts on the part of industry as well as politicians and investors. The scenario is based on the Hydrogen Council's Hydrogen Roadmap. (Fuel Cells and Hydrogen 2 Joint Councils 2019: 15, 46) The assumptions regarding fleet growth for FCEVs are significantly more optimistic than in the first Scenario. In 2050, the assumed share of passenger cars (LDVs) is just under 15%, that of LCVs and trucks (MCV & HCV) slightly below 20%, and

[2] Fuel Cells and Hydrogen 2 Joint Councils 2019: 46; ACEA 2021a: 2, 2021b: 2, 2021c: 2, 2021d: 2; BloombergNEF 2020; European Commission/Primes 2021

that of the bus fleet at around 30%. With regard to the years 2030 and 2035, for some vehicle segments it is even more optimistic than the third scenario, the decarbonisation scenario.

Table 10: FCEV share of different vehicle fleet segments in the "decarbonisation scenario" (BloombergNEF 2020)

2050 decarbonisation scenario - fuel cell fleet	2019	2030	2035	2040	2045	2050
Light-duty vehicle (LDV)	0.0%	0.2%	2.1%	9.5%	17.3%	25.0%
Light commercial vehicle (LCV)	0.1%	0.2%	1.6%	11.0%	24.2%	37.5%
Medium & heavy commercial vehicle (MCV & HCV)	0.0%	0.2%	2.3%	18.4%	40.5%	62.5%
Bus	0.1%	4.0%	10.5%	17.0%	23.5%	30.0%

Table 10 presents the third scenario, which outlines the "decarbonisation scenario" for global road transport. This is based on the individual governments worldwide setting a target of zero tail pipe emissions and actively pursuing and achieving this through appropriate measures. At the same time, hydrogen is also being promoted in other industries for decarbonisation. (BloombergNEF 2020: 21) After 2035, in this scenario, the FCEV fleets of the individual vehicle segments show by far the strongest growth. In 2050, the assumed share of LDVs is 25%, that of LCVs at 37.5%, that of MCVs & HCVs at 62.5%, and that of the bus fleet at around 30%.

By multiplying the total number of kilometres driven by the individual vehicle segments determined in Table 7 by the respective percentage share of FCEVs in the three scenarios, the absolute number of vehicle kilometres attributable to FCEVs is calculated for each scenario.

The GREET® model is used to calculate the CO_2 emissions for the respective vehicle segments and vehicle technologies in order to determine the total CO_2 emissions per vehicle fleet. A detailed list of input data can be found in Table 2 (Chapter 3) and includes assumptions for the four vehicle segments regarding lifetime (km), vehicle weight (tonnes), payload (tonnes), number of passengers, urban share (percent), and fuel production pathway.

Another point of this master's thesis is also to shed light on the additional demand for green electricity for the predicted fuel cell fleet, depending on the scenario. In order to calculate this, the current ranges of the individual vehicle segments, which they can cover with 1 kilo of green hydrogen, are determined first.

Table 11: H_2 fuel consumption of FCEV fleet segments (own compilation based on several sources[3])

Fuel cell vehicle segment	2019	2025	2030	2035	2040	2045	2050
	kg/100km						
Fuel cell LDV Consumption improvment	0.88	0.55	0.52 -5.0%	0.50 -4.0%	0.49 -3.0%	0.48 -2.0%	0.47 -1.0%
Fuel cell LCV Consumption improvment	1.00	0.70	0.67 -7.5%	0.62 -5.5%	0.59 -3.0%	0.58 -2.0%	0.58 -1.0%
Fuel Cell MCV & HCV Consumption improvment	8.11	7.50	7.13 -7.5%	6.59 -6.5%	6.10 -4.5%	5.64 -2.0%	5.22 -1.0%
Fuel cell bus Consumption improvment	7.57	7.00	6.65 -7.5%	6.15 -6.5%	5.69 -4.5%	5.26 -2.0%	4.87 -1.0%

Table 11 provides an overview of the H_2 fuel consumption of the four fuel cell vehicle segments. The data used for the range (kg/100 km) is only partly taken from literature sources, partly from commissioned studies and from the companies themselves. The reason for this approach is that there are only a very limited number of models and suppliers on the market in the fuel cell passenger car space to date and that, for example, fuel cell trucks and light commercial FCEVs are almost exclusively prototypes. (Khanna et al. 2020: 11; DOE 2021: online)

The Toyota Mirai serves as a proxy for the LDV segment. According to the company, it was able to cover 1,003 km with a 5.6 kg tank in 2021, resulting in a consumption of 0.55 kg/100 km. (Toyota 2021: online) This value is also used as an assumption in our calculations for the consumption of fuel cell passenger cars for the year 2025. The year 2025 serves exclusively as a base reference for the calculations of the fuel efficiency of the other periods included in the table and is not included in any other calculations. For the year 2019, which has no material relevance in view of the fact that there were only 24 hydrogen cars in Austria at the beginning of 2019 and 41 hydrogen cars at the end of 2019, the fuel

[3] Toyota 2021: online; ADAC 2022: online; Fuel Cells and Hydrogen 2 Joint Undertaking 2021: 66; Khanna et al. 2020: 11; Deloitte 2020: 13; Hyundai 2021: online; Liu et al. 2018: 8; FCH JU 2017: 5

consumption for LDVs was assumed to be 0.89 kg/100 km. The basis for this is a report by FCH JU. (FCH JU 2017: 5, Statistik Austria 2019: 1)

In the LCV segment, the Hyundai Nexo acts as a proxy, with a fuel consumption of 1 kg/100 km. (ADAC 2022: online) For 2025, a 30% improvement to 0.7 kg/100 km was assumed, which is still more than 25% weaker than the improvement of the fuel cell LDV.

In the FCEV heavy duty truck segment, a study by FCH JU shows a consumption of 5-9 kg/100 km for 2015-2020 models, while other studies see consumption at 7.5 kg/100 km. (Fuel Cells and Hydrogen 2 Joint Undertaking 2021: 66; Khanna et al. 2020: 11) For the year 2025, a value of 7.0 kg/100 km is assumed in this master thesis.

For buses, the source refers on the one hand to a city bus from Hyundai in Munich with a consumption of 6.8 kg/100 km. (Hyundai 2021: online), on the other hand to a study about fuel cell buses in China. The latter shows an average consumption of 7.5 kg/100 km with a variation of 5.8-8.5 kg/100 km. (Liu et al. 2019: 8) In the subsequent calculations for the consumption of the FCEV bus fleet, a value of 7.0 kg/100 km is assumed for the year 2025.

For the forecast years 2030 to 2050, an improved fuel efficiency (kg/100 km) can be assumed, as firstly the fuel cell system costs will improve significantly, and secondly the weight of the vehicles is expected to fall thanks to lighter materials, among other things. (Kim et al. 2016: 8) This circumstance is taken into account in the forecasts, but a decreasing rate of improvement is assumed for the respective subsequent periods.

5) Results

5.1 Results from the GREET® model

Table 12 shows a comparison of the total transport-related CO_2 emissions of the Austrian transport sector determined with the GREET® model and the data of the Austrian Umweltbundesamt for the year 2019. This reveals a small deviation of less than 2%, while those of the individual vehicle segments are more significant. The largest deviations come from the LCV fleet (43.7%) and bus fleet (62%), which, however, together only account for just under 9% of total CO_2 emissions in the data from the Austrian Umweltbundesamt and 12.5% in the GREET® model. The deviations in the three most important vehicle segments LDV-Otto (9.4%), LDV-Diesel (-5.2%) and MCV & HCV (-7.2%), which are responsible for about 90% of the total CO_2 emissions in the Austrian transport sector, are each less than 10%. So overall, the data from the GREET® model is found suitable for further calculations.

Table 12: Comparison of CO_2 emissions for the Austrian transport sector - Umweltbundesamt vs GREET
(Austrian Umweltbundesamt 2021; GREET® model 2021)

Vehicle Segment	Umweltbundesamt 2019	Greet 2019	Difference
	CO_2 in thousand metric tonnes		
LDV Otto fleet	4,672	5,110	9.4%
LDV Diesel fleet	9,687	9,185	-5.2%
LCV fleet	1,680	2,415	43.7%
MCV & HCV fleet	7,064	6,554	-7.2%
Bus fleet	368	596	62.0%
Total fleet emissions	**23,471**	**23,859**	**1.7%**

The CO_2 emissions calculated using the GREET® model for the respective years (2025-2050) form the basis for the further calculations. It is important to note here that the FCEVs are based on the assumption that the hydrogen was produced in an electrolysis process using electricity from renewable sources only and that CO_2-free energy is used to transport the hydrogen to the HRS. Since there are no emissions at the point of use either, the only CO_2 emissions come from the vehicle cycle, i.e. production, in the form of assembling, decommissioning, and recycling.

In the case of ICEs, on the other hand, CO_2 emissions are produced along the entire life cycle (WTW).

Table 13: CO_2 emissions for the Austrian transport sector (GREET® model 2021)

Vehicle segment	2019	2030	2035	2040	2045	2050
	gram CO_2 per km					
LDV Otto	225.1	186.5	165.8	153.7	153.5	153.8
LDV Diesel	208.5	192.9	168.2	160.3	160.1	160.4
Fuel cell LDV	47.5	39.0	37.9	37.4	37.1	36.8
LCV gasoline E10	312.4	259.5	233.7	213.2	212.9	213.2
Fuel cell LCV	64.3	51.1	49.5	48.2	47.6	47.3
MCV - Diesel	816.8	700.0	667.9	667.0	666.1	597.6
HCV - Diesel	1,262.1	882.4	804.8	803.8	802.7	729.3
Fuel cell MCV	54.6	50.0	48.8	48.3	47.8	47.4
Fuel cell HCV	85.0	76.9	74.9	74.0	73.1	72.4
School bus - Diesel	1,011.3	975.8	928.2	927.0	925.7	860.1
Transit bus - Diesel	1,234.2	1,090.5	1,047.6	1,046.0	1,044.4	952.0
Fuel cell bus	51.0	43.4	41.5	40.6	39.7	39.1

Table 13 shows that CO_2 emissions are gradually decreasing over time for all four vehicle segments, which at the same time reduces the potential savings in 2050 from substituting ICEs with FCEVs compared to 2019. There are several reasons for this, such as (i) more efficient and thus cleaner technologies in operation, (ii) new maximum permitted CO_2 limits for vehicles in the EU from 2021 (see chapter 4, section $LCOH_2$), (iii) declining emissions in the production and recycling of vehicles. For example, FCEVs running on green hydrogen do not emit CO_2 at the point of use, but they show a decrease in CO_2 emissions at the vehicle cycle. A detailed breakdown of the components that make up the total CO_2 emissions is given for all vehicle segments in the appendix.

However, the CO_2 emissions for the entire fleet of a vehicle category (LDVs, LCVs, MCVs, HCVs and buses) themselves fall much less sharply than the CO_2 emissions for the individual vehicle types. This is due to the fact that, from today's perspective, the number of vehicle kilometres will continue to increase over the next three decades (see lower section in Table 7 as well as Figure 18), thus cancelling out part of the technologically induced CO_2 emission reductions on an absolute basis.

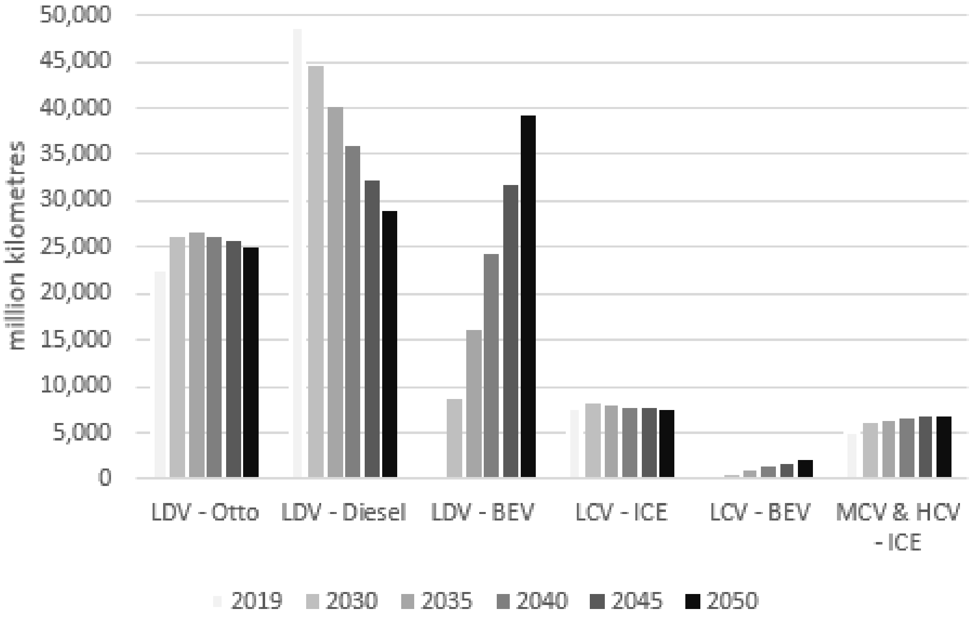

Figure 18: Austrian annual vehicle kilometres (Austrian Umweltbundesamt 2021)

Figure 18 shows that the annual vehicle kilometres driven develop differently depending on the vehicle technology. As already stated at the beginning of chapter 5, these will decline for fossil fuel vehicles in all four segments from 2035 at the latest, with the exception of trucks (MCV & HCV). These declines will be more than compensated for by significant growth in the BEV fleet in the affected vehicle segments.

The annual vehicle kilometres determined for the individual vehicle fleets (LDVs, LCVs, MCVs, HCVs and buses) in Austria are now used in equation (5.1) to calculate the vehicle kilometres of the fuel cell fleet for the four vehicle segments for each of the three scenarios described above.

The calculation of the vehicle kilometres of the fuel cell fleet is:

$$DD_{FCEV\_fleet\_seg} = DD_{fleet} * FCEV_{fleet\_pct} \quad (6)$$

where $DD_{FCEV\_fleet\_seg}$ is driving distance of fuel cell vehicle (mn km), DD_{fleet} is driving distance of total fleet (mn km) and $FCEV_{fleet\_pct}$ is the assumed FCEV's share of the total fleet (percent)

Table 14: Fuel cell electric verhicle fleet (mn km; own calculations)

2050 base scenario (million km)	2019	2030	2035	2040	2045	2050
Fuel cell LDV	0.3	17	77	481	1,284	1,898
Fuel cell LCV	-	10	15	42	92	155
Fuel Cell MCV & HCV	-	3	19	57	104	153
Fuel cell bus	-	6	13	18	25	33
2050 ambitious scenario (million km)	**2019**	**2030**	**2035**	**2040**	**2045**	**2050**
Fuel cell LDV	0.3	1,130	3,008	5,639	8,829	13,601
Fuel cell LCV	-	132	368	691	1,139	1,870
Fuel Cell MCV & HCV	-	23	83	265	656	1,255
Fuel cell bus	-	8	38	66	107	173
2050 decarbonisation scenario (million km)	**2019**	**2030**	**2035**	**2040**	**2045**	**2050**
Fuel cell LDV	0.3	159	1,706	8,205	15,467	23,258
Fuel cell LCV	-	14	142	994	2,270	3,634
Fuel Cell MCV & HCV	-	12	0	1,100	2,518	4,044
Fuel cell bus	-	22	59	97	134	172

The results are shown in Table 14. There are significant differences depending on the scenario in both the growth rate and the total annual kilometres of the individual FCEV fleets. For passenger cars (LDVs), the absolute numbers for 2050 range from 1.9 bn km in the "base scenario" to 23.3 bn km in the "decarbonisation scenario". In the LCV segment, the range is from 155 mn km in the "base scenario" to 3.6 bn km in the "decarbonisation scenario". For trucks (MCV & HCV), the kilometres driven are 153 mn in the "base scenario" and 4.0 bn km in the "decarbonisation scenario". The bus fleet is the least significant. Here, the FCEV buses account for 33 mn km in the "base scenario" and 172 mn in the "decarbonisation scenario" in 2050.

In a next step (Table 15-17), the CO_2 emissions of the entire fleet are calculated for each of the four vehicle segments. For this purpose, the CO_2 emissions (grams of CO_2 per km) listed in Table 13 for the vehicle technology of the respective vehicle segment (e.g. LDV Otto) are multiplied by the corresponding annual kilometres (Table 7) for the same vehicle technology of the same vehicle segment (again LDV Otto). This calculation is performed for all ICE and fuel cell electric vehicles of each vehicle segment.

The calculation of the CO_2 emissions per vehicle technology of a vehicle segment is as follows:

$$CO_{2\_fleet\_seg} = CO_{2\_VT\_VS} * DD_{VT\_VS} \quad (7)$$

where $CO_{2\_fleet\_seg}$ are the total CO_2 emissions per vehicle technology of a vehicle segment, $CO_{2\_VT\_VS}$ are the CO_2 emissions (grams of CO_2 per km) for the vehicle technology (VT) of the respective vehicle segment (VS) and DD_{VT_VS} is the total driving distance (mn km) of the vehicle technology (VT) of the respective vehicle segment (VS)

In a final step, the amount of CO_2 (in tonnes) that can be avoided by substituting ICEs with FCEVs is calculated. This is done by subtracting the total CO_2 emissions of the respective FCEV fleet for each vehicle segment (e.g. LDV Otto) from the total CO_2 emissions of their ICE counterparts.

The calculation of the CO_2 emissions avoidance per vehicle technology of a vehicle segment is as follows:

$$CO_{2\_AVOI\_Fleet\_Seg} = CO_{2\_fleet\_seg\_ICE} - CO_{2\_fleet\_seg\_FCEV} \quad (8)$$

where $CO_{2\_AVOI\_Fleet\_Seg}$ is total CO_2 emissions avoidance per vehicle technology of a vehicle segment resulting from the growth of the fuel cell fleets (tonnes), $CO_{2\_fleet\_seg\_ICE}$ is the total CO_2 emissions of a ICE fleet of a vehicle segment (tonnes) and $CO_{2\_fleet\_seg\_FCEV}$ is the total CO_2 emissions of the FCEV fleet of the same vehicle segment (tonnes)

This results in the following CO_2 savings for the three scenarios examined (in metric tonnes):

Table 15: "Base scenario" - GREET CO_2 emissions and CO_2 avoidance in thousand metric tonnes (GREET® model 2021 and own calculations)

Vehicle Segment		2019	2030	2035	2040	2045	2050
		CO_2 emissions in thousand metric tonnes (based on total annual vehicle kilometres per vehicle fleet)					
Light-duty vehicle (LDV)	Otto fleet	5,110	4,887	4,394	3,997	3,851	3,699
	Diesel fleet	10,177	8,582	6,742	5,696	5,035	4,476
	Emissions avoidance by replacing ICEs with FCEVs	0	-3	-10	-59	-158	-235
Light commercial vehicle (LCV)	LCV fleet	2,415	2,083	1,849	1,647	1,607	1,569
	Emissions avoidance by replacing ICEs with FCEVs	-2	-2	-3	-7	-15	-26
Medium & heavy commercial vehicle (MCV & HCV)	MCV & HCV fleet	6,554	6,214	6,114	6,458	6,696	6,181
	Emissions avoidance by replacing ICEs with FCEVs	0	-2	-13	-39	-71	-93
Bus	Bus fleet	596	562	535	531	521	465
	Emissions avoidance by replacing ICEs with FCEVs	-1	-6	-12	-17	-23	-28
Total	**Fleet emissions (without FCEV)**	**24,851**	**22,327**	**19,635**	**18,329**	**17,709**	**16,390**
	Emissions avoidance by replacing ICEs with FCEVs	**-4**	**-12**	**-37**	**-122**	**-267**	**-382**

Table 15 shows the results of the calculated CO_2 emissions for the Austrian transport sector (excluding rail, shipping, and mopeds & motorcycles). For the entire vehicle fleet of all covered vehicle technologies, these amount to 16.4 mn tonnes in 2050. This is equivalent to a decrease of around 34% compared to 2019 and is primarily due to the increasing share of BEVs and to a smaller extent lower CO_2 emissions from ICEs. As the fleet penetration of FCEVs in this scenario is well below 10% across all four vehicle segments, their overall contribution in the sense of CO_2 avoidance is only 382k tonnes. This amounts to a reduction in transport-related CO_2 emissions of less than 2% compared to 2019 level. Within the FCEV segments, the bulk of the total savings comes from the LDV segment at nearly 62%, followed by MCV & HCV at approximately 24%.

Table 16: "Ambitious case" - GREET CO_2 emissions and CO_2 avoidance in thousand metric tonnes (GREET® model 2021 and own calculations)

Vehicle Segment		2019	2030	2035	2040	2045	2050
		CO_2 emissions in thousand metric tonnes (based on total annual vehicle kilometres per vehicle fleet)					
Light-duty vehicle (LDV)	Otto fleet	5,110	4,887	4,394	3,997	3,851	3,699
	Diesel fleet	10,177	8,582	6,742	5,696	5,035	4,476
	Emissions avoidance by replacing ICEs with FCEVs	0	-174	-392	-693	-1,086	-1,681
Light commercial vehicle (LCV)	LCV fleet	2,415	2,083	1,849	1,647	1,607	1,569
	Emissions avoidance by replacing ICEs with FCEVs	-2	-28	-68	-114	-188	-310
Medium & heavy commercial vehicle (MCV & HCV)	MCV & HCV fleet	6,554	6,214	6,114	6,458	6,696	6,181
	Emissions avoidance by replacing ICEs with FCEVs	0	-18	-58	-186	-460	-765
Bus	Bus fleet	596	562	535	531	521	465
	Emissions avoidance by replacing ICEs with FCEVs	-1	-5	-11	-15	-20	-150
Total	Fleet emissions (without FCEV)	24,851	22,327	19,635	18,329	17,709	16,390
	Emissions avoidance by replacing ICEs with FCEVs	**-4**	**-225**	**-529**	**-1,008**	**-1,755**	**-2,906**

The results of the "ambitious scenario" are shown in Table 16. In this scenario, the fleet penetration of FCEVs in 2050 is between 14.6% and 30.2% depending on the vehicle segment, resulting in overall CO_2 emission savings of around 2.9 mn tonnes. This results in a 11.7% reduction in transport-related CO_2 emissions compared to the level of 2019. Within the four FCEV segments, the majority of the total savings again come from the LDV segment at nearly 58%, again followed by the MCV & HCV at slightly above 26%.

Table 17: "Decarbonisation case" - GREET CO_2 emissions and CO_2 avoidance in thousand metric tonnes (GREET® model 2021 and own calculations)

Vehicle Segment		2019	2030	2035	2040	2045	2050
		CO_2 emissions in thousand metric tonnes (based on total annual vehicle kilometres per vehicle fleet)					
Light-duty vehicle (LDV)	Otto fleet	5,110	4,641	3,308	1,712	568	0
	Diesel fleet	10,177	8,151	5,075	2,439	743	0
	Emissions avoidance by replacing ICEs with FCEVs	0	-24	-252	-1,049	-1,799	-2,707
Light commercial vehicle (LCV)	LCV fleet	2,415	2,083	1,849	1,647	1,607	1,569
	Emissions avoidance by replacing ICEs with FCEVs	-2	-3	-26	-164	-375	-603
Medium & heavy commercial vehicle (MCV & HCV)	MCV & HCV fleet	6,554	6,214	6,114	6,458	6,696	6,181
	Emissions avoidance by replacing ICEs with FCEVs	0	-9	0	-750	-1,714	-2,466
Bus	Bus fleet	596	562	535	531	521	465
	Emissions avoidance by replacing ICEs with FCEVs	-1	-22	-56	-91	-127	-149
Total	Fleet emissions (without FCEV)	24,851	21,650	16,881	12,788	10,134	8,215
	Emissions avoidance by replacing ICEs with FCEVs	**-4**	**-57**	**-334**	**-2,054**	**-4,015**	**-5,925**

As presented in Table 17, the impact is greatest in the "decarbonisation case". Here, fleet penetration is between 25% and 62.5% depending on the vehicle segment, resulting in overall CO_2 emission savings of around 5.9 mn metric tonnes. This results in a reduction in transport-related CO_2 emissions of almost a quarter (-23.8%) compared to 2019 level. Within the four FCEV segments, the largest share of savings again comes from passenger cars (LDVs) at almost 46%, closely followed by MCV & HCV at nearly 42%. This is despite the fact that the MCV & HCV fleet has a market penetration of 62.5% in this scenario compared to 25% for LDVs. The explanation for this is that the LDV fleet in 2050 will complete almost 14 times as many vehicle kilometres as heavy commercial vehicles (see Table 7).

5.2 Electricity demand calculation

In the following, the additional renewable energy demand that would result from the growth of the FCEV fleet in Austria is calculated for each scenario. The starting point is the vehicle kilometres of the four fuel cell vehicle segments for the years 2030-2050 previously calculated in Table 14. These are multiplied by the hydrogen demand (kg/100 km) determined in Table 11 for the respective FCEV segment.

The calculation for the H_2 fuel demand per FCEV fleet segment is as follows:

$$C_{H_2 fleet\_seg} = DD_{FCEV\_fleet\_seg} * C_{H_2 FCEV\_seg\_avg} \quad (9)$$

where $C_{H_2 Fleet\_seg}$ is the total H_2 fuel consumption (kg) per FCEV fleet segment, $DD_{FCEV\_Fleet\_seg}$ is the total driving distance per FCEV fleet segment (mn km) and $C_{H_2 FCEV\_seg\_avg}$ is the average H_2 fuel consumption of an FCEV from the same vehicle segment (kg per km)

Table 18: H_2 fuel demand per FCEV-vehicle fleet segment (amid FCEV growth; own calculations)

2050 base scenario (tonnes H_2)	2019	2030	2035	2040	2045	2050
Fuel cell LDV	3	89	385	2,340	6,120	8,961
Fuel cell LCV	-	63	93	250	536	895
Fuel Cell MCV & HCV	-	189	1,220	3,482	5,847	7,980
Fuel cell bus	-	371	777	1,008	1,298	1,587
Total	**3**	**712**	**2,475**	**7,080**	**13,801**	**19,423**

2050 ambitious scenario (tonnes H_2)	2019	2030	2035	2040	2045	2050
Fuel cell LDV	3	5,905	15,090	27,438	42,097	64,204
Fuel cell LCV	-	880	2,287	4,104	6,628	10,772
Fuel Cell MCV & HCV	-	1,646	5,438	16,182	36,982	65,446
Fuel cell bus	-	512	2,315	3,729	5,606	8,422
Total	**3**	**8,943**	**25,130**	**51,453**	**91,313**	**148,846**

2050 decarbonisation scenario (tonnes H_2)	2019	2030	2035	2040	2045	2050
Fuel cell LDV	3	829	8,555	39,922	73,748	109,789
Fuel cell LCV	-	91	881	5,900	13,207	20,937
Fuel Cell MCV & HCV	-	840	0	67,085	141,970	210,946
Fuel cell bus	-	1,478	3,633	5,496	7,075	8,370
Total	**3**	**3,237**	**13,069**	**118,403**	**236,000**	**350,042**

Table 18 now shows the results of the total H_2 fuel demand of both the individual vehicle segments and the entire FCEV fleet in each of the three scenarios. While the demand for the entire FCEV fleet in the “base scenario” is below 20k tonnes of H_2, it is already 149k tonnes of H_2 in the "ambitious scenario" and even 350k tonnes in the "decarbonisation scenario".

In a final step, the quantities of renewable energies required to produce the previously calculated annual H_2 fuel demand with the respective vehicle fleet can now be calculated.

For this calculation, however, the efficiency losses along the process chain from hydrogen production to transport to the refuelling station ("well-to-tank") must be taken into account here. In the literature, the energy efficiency of this process is reported to range from 42-57%. (Perez et al. 2021: 3)

WELL-TO-WHEEL (WTW)	WELL-TO-TANK (WTW)	Energy	100%
		Electrolysis	70%
		Compression & liquefication	61,6%
		Transportation & filling	49,3%
		Fuel cell & power generation	32%
	TANK-TO-WHEEL (TTW)	Electric battery E-engine	30% overall efficiency

Figure 19: Overall efficiency of a fuel cell vehicle (Volkswagen AG 2019: online)

As shown in figure 19, Volkswagen sees the well-to-tank efficiency rate at 32%. The company expects an electrolyser efficiency of 70% here. The other processes, such as compression & liquification and transportation & filling, lead to further losses totaling just under 51%, leaving a good 49% available for refuelling at the hydrogen refuelling station. (Volkswagen 2019: online)

As stated in chapter 2, ITM Power sees the efficiency of PEM technology at 77%. (expert interview, December 2021) If the Volkswagen figures are adjusted to the higher efficiency of the electrolysers stated by ITM Power, this results in 54.2% of the initial electricity quantity at the pump i.e. the efficiency losses amount to 45.8%. This means that to provide 1 kilo of green hydrogen at the pump, almost twice the amount of renewable energy will be needed as 1 kilo of hydrogen contains in energy.

Therefore, in the final step, the demand for renewable energies resulting from the growth of the fuel cell fleet is calculated in the form of kilowatt hours. For this purpose, the previously determined hydrogen fuel demand in kilogrammes is increased by the efficiency losses from process chain of 45.8% and multiplied by the energy content of hydrogen (HHV_{H_2}=$39.4\ kWh/kg$).

The calculation for the total electricity demand is as follows:

$$E = \sum_{n=1}^{n} HHV_{H_2} \left(\frac{C_{H_2 fleet\_seg}}{(1-L_{PCT})} \right) \tag{10}$$

where E is the total electricity demand resulting from the growth of the FCEV fleet (GWh), $C_{H_2 fleet\_seg}$ is the total H_2 fuel consumption per FCEV segment (kg), L_{PCT} is the efficiency loss along the path to the pump (in percent) and HHV_{H_2} is the higher heating value of hydrogen (kWh/kg), n is the number of the fleet segments

Table 19: Electricity demand of the fuel cell fleet in GWh (own calculations)

2050 base scenario	2019	2030	2035	2040	2045	2050
Total GWh/year	**0.2**	**52**	**180**	**514**	**1,003**	**1,411**
2050 ambitious scenario	2019	2030	2035	2040	2045	2050
Total GWh/year	**0.2**	**650**	**1,826**	**3,738**	**6,634**	**10,814**
2050 decarbonisation scenario	2019	2030	2035	2040	2045	2050
Total GWh/year	**0.2**	**235**	**950**	**8,602**	**17,146**	**25,432**

Table 19 presents the additional electricity demand for renewables resulting from the growth of the fuel cell vehicle fleet in each scenario.

The results show that the “base scenario” would result in an additional electricity demand of 1.4 TWh in 2050.

In the "ambitious scenario" it would be 10.8 TWh, almost eight times as much as in the "base scenario".

The "decarbonisation scenario" would lead to an additional demand of 25.4 TWh and thus approximately 18 times the demand of the "base scenario".

To put these figures into perspective, it makes sense to look at the current electricity consumption in Austria. This amounted to around 74 TWh in 2018. (IG Windkraft 2021: 4) Thus, it is clear that only the “ambitious scenario” and the “decarbonisation scenario” would have a significant impact on Austria's electricity consumption. In the “base scenario”, on the other hand, electricity demand would increase by less than two percent and could easily be met from additional renewable energy capacities.

However, especially in the most optimistic scenario and somewhat less clearly in the "ambitious scenario", the impact on the Austrian electricity demand would be quite significant, the electricity demand would increase by more almost 35% and approximately 15%, respectively, compared to 2018. The increase in the optimistic scenario would almost be as big as the expansion targets for renewables of 27 TWh by 2030 set out in the Renewable Energy Expansion Act. (Parliament of the Republic of Austria 2021: 6)

In addition, if Europe were to develop towards a hydrogen economy, it must be assumed that other industrial sectors would also have a massively higher demand for green hydrogen. The Austrian steel company VOEST is currently running a pilot project "H2FUTURE" with PEM technology and a size of 6 MW. The company has calculated from their own data that a complete conversion of their steel production to hydrogen-based steel production would result in an additional electricity demand of 33 TWh, more than the additional hydrogen demand that would come from the "decarbonisation scenario” calculated in this paper and even more than expansion targets for renewables of 27 TWh by 2030 set out in the Renewable Energy Expansion Act. (VOEST 2019: 3, 6; Parliament of the Republic of Austria 2021: 6)

6. Conclusions

Green hydrogen indisputably offers the ingredients to make a significant contribution to decarbonising parts of the economy. Solar and wind are available in more than sufficient quantities, and the electricity production costs from solar and onshore wind are already cheaper than those from fossil fuels in large parts of the world. For offshore wind, such a scenario is realistic within this decade. Water, an important resource for the electrolysis of green hydrogen to decarbonise transport, remains a much-discussed topic. In principle, water resources are of course very large, but geographically unevenly distributed. The quantities of water required for a significant growth of green hydrogen must of course be critically questioned from an ecological point of view, but one can certainly argue that the positive effects of green hydrogen with regard to a reduction of greenhouse gases outweigh the negative effects of an additional water requirement.

The question of whether green hydrogen will play a significant role in the Austrian transport sector in the coming decades can only be answered to a limited extent from today's perspective. It seems obvious that FCEVs will only play a very minor role in the next 10 years and will not be able to make a meaningful contribution to the CO_2 emission reduction targets of e.g. the European Union of at least 55% by 2030 (compared to the base year 1990).

However, taking a look at the next decade from 2031-2040 paints a much more exciting picture. By then, both the costs of producing electrolyser plants and those of the fuel cell itself could have fallen significantly thanks to economies of scale and technological progress. In addition, there is a high probability that the cost of electricity from renewables such as solar and wind should continue to fall relative to fossil-based power generation costs. This effect is likely to be reinforced by a higher CO_2 tax or higher CO_2 certificate prices in the coming decades.

The last point also brings us back to politics. The EU and many European governments have now committed themselves to a hydrogen economy. (IEA 2021a: 27-29, 183-187) Unfortunately, despite its announcement to present a hydrogen strategy in 2021, the Austrian government has failed to put this into practice so far. As a result, it runs the risk of falling behind other countries. In the end, at any rate, the political decision-makers will have to prove that their plans regarding a hydrogen economy are not just lip service. Without very high investments in a hydrogen infrastructure as well as subsidies for the purchase of a fuel cell vehicle it seems very difficult to imagine that a critical mass can be reached, especially in the passenger sector. The CO_2 tax already mentioned can have an important leverage effect - at least relative to ICEs. But of course, BEVs also benefit from the higher CO_2 prices, so that in the passenger car segment in particular, the advantage of BEVs in terms of lower total cost of ownership remains, also thanks to their higher energy efficiency. In addition, BEVs simply have a head start in terms of time, which is noticeable both in the manufacturing costs of the BEV and in terms of infrastructure. The significantly shorter charging times and longer range of FCEVs will probably not be able to compensate for this shortcoming in the passenger car segment from the customer's point of view.

The prospects for medium and heavy commercial vehicles and buses appear much more interesting. In addition to the longer refuelling time and shorter range, the weight of the battery also has a negative impact on BEV models. In addition, trucks usually require a less dense HRS network than is the case with fuel cell passenger cars. From today's perspective, at least in the medium and heavy vehicle segment, it seems unlikely that a "winner takes it all" market situation will arise. It is much more likely that both technologies, BEV and FCEV, will coexist in these vehicle segments.

Looking ahead to 2050, it certainly seems plausible from today's perspective that FCEVs will be able to find their place within the commercial vehicle segment space.

In any case, the results of this master's thesis have shown that, in an admittedly very optimistic scenario, FCEVs could reduce transport-related CO_2 emissions in Austria by almost a quarter in 2050 compared to 2019. At the same time, however, this would also result in an increase in Austrian electricity demand of a around 35% compared to 2019. In order to be able to meet an increasing demand for green hydrogen due to a possible significant growth in fuel cell electric cars, but also due to a growing demand from other industries, the further expansion of renewable energy capacities must be given high priority. Thanks to its large hydropower capacities, Austria is fortunate to already be able to draw on large amounts of renewable energies in its electricity generation. These must be further expanded, above all in the solar and wind space. This in turn would be a good basis for making the economy hydrogen-compatible. By all means, green hydrogen offers a great opportunity to play its part in decarbonising the transport sector. In view of the rapidly progressing global warming and the consequences that can already be felt and seen today and that will in all likelihood intensify in the future, all possibilities including green hydrogen should be pursued as an environmentally friendly technology in the transport sector instead of focusing on a few technologies only.

It is not without reason that the IEA sees green hydrogen as a piece of the puzzle in achieving net zero emissions by 2050.

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List of abbreviations

BEV	battery electric vehicle
bn	billion
CCS	carbon capture & storage
CCUS	carbon capture, utilisation and storage
CO_2	carbon dioxide
CO_{2eq}	carbon dioxide equivalent
CCGT	combined cycle gas turbine
CAGR	compounded annual growth
C2G	cradle-to-grave
FCEV	fuel cell electric vehicle
g	gram
GW	gigawatt
GHG	greenhouse gas
GREET	Greenhouse gas, Regulated Emissions, and Energy use in Transportation
H_2	Hydrogen
HCV	heavy commercial vehicle
HHV	higher heating value
hkm	hundred kilometres
HRS	hydrogen refuelling stations
ICE	internal combustion engine
k	thousand
kg	kilogramme
km	kilometre
kW_e	kilowatt-electric
kWh	kilowatt hour
LCOE	levelized cost of electricity
$LCOH_2$	levelized cost of hydrogen
LCV	light commercial vehicle
LDV	light-duty vehicle
MCV	medium commercial vehicle
MJ	megajoule
MW	megawatt
MWh	megawatt hour
m^2	square metre
mn	million
NHS	National hydrogen strategy
NZE	net zero emissions
O&M	operation & maintenance
p.a.	per annum
ppm	parts per million

PHEV	Plug-in hybrid electric vehicle
PEM	proton exchange membrane
SOEC	solid oxide electrolysis cell
SMR	steam methane reforming
TWh	terawatt hour
t CO_{2eq}	tonnes of CO_2 equivalent
TCO	total cost of ownership
WTP	well-to-pump
WTT	well-to-tank
WTW	well-to-wheel

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Appendix – part A

Part A of the appendix deals with the results of the TCO calculations in detail.

TCO assumptions for the four vehicle segments (LDV, LCV, truck, and bus) at today's prices (own compilation based on several sources[4])

TCO values today	Light-duty vehicle (LDV)			Light commercial vehicle (LCV)		
	FCEV	BEV	ICE Gasoline	FCEV	BEV	ICE Gasoline
Initial purchase price (EUR)	59,437	36,496	27,985	77,939	40,943	34,617
Fuel price FCEV (EUR/kg H_2) **Fuel economy FCEV** (km/kgH_2)	7.0 119.05			7.0 100.00		
Fuel price BEV (EUR/kWh) **Fuel economy BEV** (km/kWh)		0.21 6.99			0.21 7.14	
Fuel price ICE (EUR/litre) **Fuel economy ICE** (km/litre)			1.29 17.54			1.29 15.63
Maintenance costs (EUR/km)	0.08	0.07	0.05	0.07	0.07	0.05
Insurance costs per year (EUR)	351	267	876	351	323	1,107
Vehicle kilometres per year (km)	15,000			15,000		
Lifetime (years)	10			10		
Residual value	10%			10%		
Discount rate	10%			10%		
Consumer Price Index	1.5%			1.5%		

TCO values today	Heavy-duty truck			Bus		
	FCEV	BEV	ICE Diesel	FCEV	BEV	ICE Diesel
Initial purchase price (EUR)	312,949	386,938	87,000	635,705	399,082	284,302
Fuel price FCEV (EUR/kg H_2) **Fuel economy FCEV** (km/kgH_2)	7.0 11.76			7.0 13.21		
Fuel price BEV (EUR/kWh) **Fuel economy BEV** (km/kWh)		0.21 0.74			0.16 0.58	
Fuel price ICE (EUR/litre) **Fuel economy ICE** (km/litre)			1.23 3.03			1.23 2.58
Maintenance costs (EUR/km)	0.12	0.11	0.13	0.18	0.18	0.22
Insurance costs per year (EUR)	1,878	2,322	522	6,217	4,458	2,929
Vehicle kilometres per year (km)	140,000			40,000		
Lifetime (years)	10			10		
Residual value	10%			10%		
Discount rate	10%			10%		
Consumer Price Index	1.5%			1.5%		

[4] Fuel Cells and Hydrogen 2 Joint Undertaking 2021: 327-329, 332, 343, 345, 347; Deloitte 2020: 44, 45; Hyundai 2021: online; Liu et al. 2018: 8; BloombergNEF 2020: 23, 24; ADAC 2022: online; ÖAMTC 2022: online; Wien Energie 2022: online; Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie 2021c: online; IEA 2019b: 11; Toyota 2021: online

This table lists all assumptions for the calculation of the current TCO of the individual vehicle technologies (FCEV, BEV, ICE) from the 4 vehicle segments examined in this master thesis and refer to the European market.

In the LDV and LCV segments, the initial purchase price for an FCEV is significantly higher than that for a BEV or ICE vehicle. Especially compared to ICE, the purchase price for a fuel cell car in the LDV segment is more than twice as high as that of an ICE vehicle, despite subsidies. (ADAC 2022: online) In the truck segment, a fuel cell truck would already be cheaper than a battery electric truck, while in the bus segment a fuel cell bus is significantly more expensive than a battery electric bus or an ICE bus. (Fuel Cells and Hydrogen 2 Joint Undertaking 2021: 327-329, 332, 343; Deloitte 2020: 44)

The assumed fuel prices for hydrogen, electricity and gasoline and diesel correspond to current market prices.

The fuel economy for a fuel cell LDV or LCV is set rather low here. Thus 119 km/kg implies that a 5-kg tank can cover just under 600 km. (ADAC 2022: online) However, Toyota has already shown with its Mirai model under test conditions that significantly longer distances can be achieved. (Toyota 2021: online) The fuel economy assumptions for battery electric LDV and LCV as well as for ICE LDV and LCV are based on ADAC data. (ADAC 2022: online) The values for the vehicle segments "truck" and "bus" are based on expert reports and studies. (Liu et al. 2018: 8; Fuel Cells and Hydrogen 2 Joint Undertaking 2021: 347, BloombergNEF: 24).

For maintenance costs, the cost differences between the individual technologies are relatively small, with ICE powered LDV and LCV and battery-powered trucks and buses have slightly lower absolute costs. (IEA 2019b: 11; ADAC 2022: online)

Insurance costs for LDVs and LCVs are based on current data from ÖAMTC and are expected to increase by an inflation rate of 1.5% p.a. over the vehicle lifetime of 10 years. The insurance costs for trucks are estimated at 0.6% of the initial purchase price. (Fuel Cells and Hydrogen 2 Joint Undertaking 2021: 347) In absolute terms, the costs are highest for buses. (Deloitte 2020: 45) The annual vehicle kilometres for LDVs and LCVS in the TCO calculations amount to 15,000 km each, those for trucks 140,000 km and those for buses 40,000 km. (ADAC 2022: online; Fuel Cells and Hydrogen 2 Joint Undertaking 2021: 345; GREET model 2021)

Subsidies are also taken into account in the calculations and are deducted directly from the initial purchase price of the affected vehicles. In Austria, the purchase of both an FCEV and a BEV will be subsidised by 5,000 euros in 2022. (Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie 2021c) However, the price of an LDV or LCV may not exceed EUR 65,000. (Kommunal Kredit Public Consulting 2021: online) Thus, from today's perspective, in the FCEV space for 2022, only the Toyota Mirai with a base price of just over EUR 60,000 is eligible, while Hyundai's Nexo model is currently offered with a base price of over EUR 77,000. (ADAC 2022: online) The situation is similar with the Austrian Normverbrauchsabgabe (NOVA). This leads to a higher initial purchase price for LDVs and LCVs powered by diesel or gasoline and is calculated using the Nova calculator of the Federal Ministry of Finance. (Bundesministerium für Finanzen 2022: online) In the case of FCEVs or BEVs, the purchaser of a vehicle is currently exempt from NOVA under the Normverbrauchsabgabegesetz (§ 3. Abs. 1 Z 1 NoVAG 1991), as these have a CO_2 emission value of 0 g/km at the point of use. (Rechtsinformationssystem des Bundes (RIS) der Republik Österreich 2022: 3)

The following is a breakdown of the individual TCO calculations for all vehicle technologies within the 4 vehicle segments analysed in this master’s thesis.

TCO calculation – Fuel cell LDV today

Assumptions	Input Data in real terms	Units
Initial purchase price (CAPEX)	59,437	EUR
Lifetime	10	years
Annual driving distance	15,000	km
Fuel price	7.00	EUR/kg
Fuel economy	119.05	km/kgH2
O&M (incl. all variable costs)	0.08	EUR/km
Insurance costs	351	EUR/year
Residual Value	10.00%	
Discount rate / cost of capital	10.00%	
CPI	1.5%	

Year	Discounted CF	Nominal CF	Fuel Costs	O&M	Insurance Costs	Residual Value
0	€ 59,437	€ 59,437				€ 59,437
1	€ 2,223	€ 2,445	€ 895	€ 1,194	€ 357	
2	€ 2,051	€ 2,482	€ 909	€ 1,212	€ 362	
3	€ 1,893	€ 2,519	€ 922	€ 1,230	€ 367	
4	€ 1,747	€ 2,557	€ 936	€ 1,248	€ 373	
5	€ 1,612	€ 2,595	€ 950	€ 1,267	€ 378	
6	€ 1,487	€ 2,634	€ 964	€ 1,286	€ 384	
7	€ 1,372	€ 2,674	€ 979	€ 1,305	€ 390	
8	€ 1,266	€ 2,714	€ 994	€ 1,325	€ 396	
9	€ 1,168	€ 2,755	€ 1,008	€ 1,345	€ 402	
10	-€ 1,581	-€ 4,102	€ 1,024	€ 1,365	€ 408	-€ 6,898
TCO	€ 72,674					
TCO per km	€ 0.48					

TCO results (EUR/km)			
TCO - Capex	TCO - Fuel costs	TCO - O&M costs	TCO - Total
€ 0.38	€ 0.04	€ 0.07	€ 0.48

The purchase price of the fuel cell LDV accounts currently for 78% of the total TCO, while fuel costs account for less than 10%.

TCO calculation – Fuel cell LDV 2030

Assumptions	Input Data in real terms	Units
Initial purchase price (CAPEX)	43,358	EUR
Lifetime	10	years
Annual driving distance	15,000	km
Fuel price	3.53	EUR/kg
Fuel economy	191.39	km/kgH2
O&M (incl. all variable costs)	0.07	EUR/km
Insurance costs	402	EUR/year
Residual Value	10.00%	
Discount rate / cost of capital	10.00%	
CPI	1.5%	

Year	Discounted CF	Nominal CF	Fuel Costs	O&M	Insurance Costs	Residual Value
0	€ 43,358	€ 43,358				€ 43,358
1	€ 1,612	€ 1,774	€ 281	€ 1,085	€ 408	
2	€ 1,488	€ 1,800	€ 285	€ 1,101	€ 414	
3	€ 1,373	€ 1,827	€ 289	€ 1,118	€ 420	
4	€ 1,267	€ 1,855	€ 294	€ 1,135	€ 426	
5	€ 1,169	€ 1,883	€ 298	€ 1,152	€ 433	
6	€ 1,079	€ 1,911	€ 303	€ 1,169	€ 439	
7	€ 995	€ 1,939	€ 307	€ 1,187	€ 446	
8	€ 918	€ 1,969	€ 312	€ 1,204	€ 452	
9	€ 847	€ 1,998	€ 316	€ 1,222	€ 459	
10	-€ 1,158	-€ 3,004	€ 321	€ 1,241	€ 466	-€ 5,032
TCO	€ 52,948					
TCO per km	€ 0.35					

TCO results (EUR/km)			
TCO - Capex	TCO - Fuel costs	TCO - O&M costs	TCO - Total
€ 0.28	€ 0.01	€ 0.06	€ 0.35

The purchase price of the fuel cell LDV in 2030 is 78% of the total TCO, while fuel costs account for less than 5%.

TCO calculation – BEV LDV today

Assumptions	Input Data in real terms	Units
Initial purchase price (CAPEX)	36,496	EUR
Lifetime	10	years
Annual driving distance	15,000	km
Fuel price	0.21	EUR/kWh
Fuel economy	6.99	km/kWh
O&M (incl. all variable costs)	0.07	EUR/km
Insurance costs	267	EUR/year
Residual Value	10.00%	
Discount rate / cost of capital	10.00%	
CPI	1.5%	

Year	Discounted CF	Nominal CF	Fuel Costs	O&M	Insurance Costs	Residual Value
0	€ 36,496	€ 36,496				€ 36,496
1	€ 1,595	€ 1,755	€ 448	€ 1,035	€ 271	
2	€ 1,472	€ 1,781	€ 455	€ 1,051	€ 275	
3	€ 1,358	€ 1,808	€ 462	€ 1,067	€ 279	
4	€ 1,253	€ 1,835	€ 469	€ 1,083	€ 283	
5	€ 1,156	€ 1,862	€ 476	€ 1,099	€ 288	
6	€ 1,067	€ 1,890	€ 483	€ 1,115	€ 292	
7	€ 985	€ 1,919	€ 490	€ 1,132	€ 296	
8	€ 909	€ 1,947	€ 498	€ 1,149	€ 301	
9	€ 838	€ 1,977	€ 505	€ 1,166	€ 305	
10	-€ 655	-€ 1,698	€ 513	€ 1,184	€ 310	-€ 3,704
TCO	€ 46,475					
TCO per km	€ 0.31					

TCO results (EUR/km)			
TCO - Capex	TCO - Fuel costs	TCO - O&M costs	TCO - Total
€ 0.23	€ 0.02	€ 0.06	€ 0.31

The cost share for the purchase price of the battery electric LDV is currently almost 76% and thus accounts for the absolute majority of the total TCO, while the fuel costs account for a very small share of the total TCO at approx. 6%.

TCO calculation – BEV LDV 2030

Assumptions	Input Data in real terms	Units
Initial purchase price (CAPEX)	31,569	EUR
Lifetime	10	years
Annual driving distance	15,000	km
Fuel price	0.09	EUR/kWh
Fuel economy	7.48	km/kWh
O&M (incl. all variable costs)	0.06	EUR/km
Insurance costs	305	EUR/year
Residual Value	10.00%	
Discount rate / cost of capital	10.00%	
CPI	1.5%	

Year	Discounted CF	Nominal CF	Fuel Costs	O&M	Insurance Costs	Residual Value
0	€ 31,569	€ 31,569				€ 31,569
1	€ 1,301	€ 1,431	€ 180	€ 941	€ 310	
2	€ 1,200	€ 1,452	€ 182	€ 955	€ 314	
3	€ 1,107	€ 1,474	€ 185	€ 970	€ 319	
4	€ 1,022	€ 1,496	€ 188	€ 984	€ 324	
5	€ 943	€ 1,518	€ 191	€ 999	€ 329	
6	€ 870	€ 1,541	€ 194	€ 1,014	€ 334	
7	€ 803	€ 1,564	€ 196	€ 1,029	€ 339	
8	€ 741	€ 1,588	€ 199	€ 1,045	€ 344	
9	€ 683	€ 1,612	€ 202	€ 1,060	€ 349	
10	-€ 605	-€ 1,568	€ 205	€ 1,076	€ 354	-€ 3,204
TCO	€ 39,634					
TCO per km	€ 0.26					

TCO results (EUR/km)			
TCO - Capex	TCO - Fuel costs	TCO - O&M costs	TCO - Total
€ 0.20	€ 0.01	€ 0.05	€ 0.26

The cost share for the purchase price of the battery electric LDV in 2030 is 77% and thus accounts for the absolute majority of the total TCO, while the fuel costs account for a very small share of the total TCO at only approx. 3%.

TCO calculation – ICE LDV today

Assumptions	Input Data in real terms	Units
Initial purchase price (CAPEX)	27,985	EUR
Lifetime	10	years
Annual driving distance	15,000	km
Fuel price	1.29	EUR/Liter
Fuel economy	17.54	km/litre
O&M (incl. all variable costs)	0.05	EUR/km
Insurance costs	876	EUR/year
Residual Value	10.00%	
Discount rate / cost of capital	10.00%	
CPI	1.5%	

Year	Discounted CF	Nominal CF	Fuel Costs	O&M	Insurance Costs	Residual Value
0	€ 27,985	€ 27,985				€ 27,985
1	€ 2,492	€ 2,741	€ 1,120	€ 731	€ 889	
2	€ 2,299	€ 2,782	€ 1,137	€ 742	€ 903	
3	€ 2,121	€ 2,823	€ 1,154	€ 753	€ 916	
4	€ 1,957	€ 2,866	€ 1,172	€ 764	€ 930	
5	€ 1,806	€ 2,909	€ 1,189	€ 776	€ 944	
6	€ 1,667	€ 2,952	€ 1,207	€ 787	€ 958	
7	€ 1,538	€ 2,997	€ 1,225	€ 799	€ 973	
8	€ 1,419	€ 3,042	€ 1,243	€ 811	€ 987	
9	€ 1,309	€ 3,087	€ 1,262	€ 823	€ 1,002	
10	€ 113	€ 293	€ 1,281	€ 836	€ 1,017	-€ 2,841
TCO	**€ 44,706**					
TCO per km	**€ 0.30**					

TCO results (EUR/km)			
TCO - Capex	TCO - Fuel costs	TCO - O&M costs	TCO - Total
€ 0.18	€ 0.05	€ 0.07	€ 0.30

For the ICE LDV, the cost of purchasing the vehicle currently accounts for around 60% of the total TCO, followed by O&M costs at just under 24% and fuel costs at 16%.

TCO calculation – ICE LDV 2030

Assumptions	Input Data in real terms	Units
Initial purchase price (CAPEX)	28,219	EUR
Lifetime	10	years
Annual driving distance	15,000	km
Fuel price	1.48	EUR/Liter
Fuel economy	24.39	km/litre
O&M (incl. all variable costs)	0.05	EUR/km
Insurance costs	366	EUR/year
Residual Value	10.00%	
Discount rate / cost of capital	10.00%	
CPI	1.5%	

Year	Discounted CF	Nominal CF	Fuel Costs	O&M	Insurance Costs	Residual Value
0	€ 28,219	€ 28,219				€ 28,219
1	€ 1,839	€ 2,023	€ 921	€ 731	€ 371	
2	€ 1,697	€ 2,054	€ 935	€ 742	€ 377	
3	€ 1,566	€ 2,084	€ 949	€ 753	€ 382	
4	€ 1,445	€ 2,116	€ 964	€ 764	€ 388	
5	€ 1,333	€ 2,147	€ 978	€ 776	€ 394	
6	€ 1,230	€ 2,180	€ 993	€ 787	€ 400	
7	€ 1,135	€ 2,212	€ 1,008	€ 799	€ 406	
8	€ 1,048	€ 2,245	€ 1,023	€ 811	€ 412	
9	€ 967	€ 2,279	€ 1,038	€ 823	€ 418	
10	-€ 212	-€ 551	€ 1,054	€ 836	€ 424	-€ 2,864
TCO	**€ 40,268**					
TCO per km	**€ 0.27**					

TCO results (EUR/km)			
TCO - Capex	TCO - Fuel costs	TCO - O&M costs	TCO - Total
€ 0.18	€ 0.04	€ 0.05	€ 0.27

For the ICE LDV, in 2030 the cost of purchasing the vehicle accounts for around 67% of the total TCO, followed by O&M costs at just under 18% and fuel costs at 15%.

TCO calculation – Fuel cell LCV today

Assumptions	Input Data in real terms	Units
Initial purchase price (CAPEX)	77,939	EUR
Lifetime	10	years
Annual driving distance	15,000	km
Fuel price	7.00	EUR/kg
Fuel economy	100.00	km/kgH2
O&M (incl. all variable costs)	0.07	EUR/km
Insurance costs	351	EUR/year
Residual Value	10.00%	
Discount rate / cost of capital	10.00%	
CPI	1.5%	

Year	Discounted CF	Nominal CF	Fuel Costs	O&M	Insurance Costs	Residual Value
0	€ 77,939	€ 77,939				€ 77,939
1	€ 2,245	€ 2,470	€ 1,066	€ 1,047	€ 357	
2	€ 2,072	€ 2,507	€ 1,082	€ 1,063	€ 362	
3	€ 1,912	€ 2,544	€ 1,098	€ 1,079	€ 367	
4	€ 1,764	€ 2,583	€ 1,114	€ 1,095	€ 373	
5	€ 1,628	€ 2,621	€ 1,131	€ 1,112	€ 378	
6	€ 1,502	€ 2,661	€ 1,148	€ 1,128	€ 384	
7	€ 1,386	€ 2,701	€ 1,165	€ 1,145	€ 390	
8	€ 1,279	€ 2,741	€ 1,183	€ 1,163	€ 396	
9	€ 1,180	€ 2,782	€ 1,201	€ 1,180	€ 402	
10	-€ 2,399	-€ 6,221	€ 1,219	€ 1,198	€ 408	-€ 9,045
TCO	€ 90,507					
TCO per km	€ 0.60					

TCO results (EUR/km)			
TCO - Capex	TCO - Fuel costs	TCO - O&M costs	TCO - Total
€ 0.50	€ 0.05	€ 0.06	€ 0.60

For the fuel cell LCV, the cost of purchasing the vehicle currently accounts for around 82% of the total TCO, followed by O&M costs at just under 10% and fuel costs at 8%.

TCO calculation – Fuel cell LCV 2030

Assumptions	Input Data in real terms	Units
Initial purchase price (CAPEX)	51,855	EUR
Lifetime	10	years
Annual driving distance	15,000	km
Fuel price	3.53	EUR/kg
Fuel economy	150.38	km/kgH2
O&M (incl. all variable costs)	0.06	EUR/km
Insurance costs	402	EUR/year
Residual Value	10.00%	
Discount rate / cost of capital	10.00%	
CPI	1.5%	

Year	Discounted CF	Nominal CF	Fuel Costs	O&M	Insurance Costs	Residual Value
0	€ 51,855	€ 51,855				€ 51,855
1	€ 1,561	€ 1,717	€ 358	€ 952	€ 408	
2	€ 1,441	€ 1,743	€ 363	€ 967	€ 414	
3	€ 1,329	€ 1,769	€ 368	€ 981	€ 420	
4	€ 1,227	€ 1,796	€ 374	€ 996	€ 426	
5	€ 1,132	€ 1,823	€ 380	€ 1,011	€ 433	
6	€ 1,044	€ 1,850	€ 385	€ 1,026	€ 439	
7	€ 964	€ 1,878	€ 391	€ 1,041	€ 446	
8	€ 889	€ 1,906	€ 397	€ 1,057	€ 452	
9	€ 821	€ 1,935	€ 403	€ 1,073	€ 459	
10	-€ 1,563	-€ 4,054	€ 409	€ 1,089	€ 466	-€ 6,018
TCO	€ 60,700					
TCO per km	€ 0.40					

TCO results (EUR/km)			
TCO - Capex	TCO - Fuel costs	TCO - O&M costs	TCO - Total
€ 0.33	€ 0.02	€ 0.06	€ 0.40

For the fuel cell LCV, in 2030, the cost of purchasing the vehicle accounts for almost 82% of the total TCO, followed by O&M costs at almost 15% and fuel costs at less than 4%.

TCO calculation – BEV LCV today

Assumptions	Input Data in real terms	Units
Initial purchase price (CAPEX)	40,943	EUR
Lifetime	10	years
Annual driving distance	15,000	km
Fuel price	0.21	EUR/kWh
Fuel economy	7.14	km/kWh
O&M (incl. all variable costs)	0.07	EUR/km
Insurance costs	323	EUR/year
Residual Value	10.00%	
Discount rate / cost of capital	10.00%	
CPI	1.5%	

Year	Discounted CF	Nominal CF	Fuel Costs	O&M	Insurance Costs	Residual Value
0	€ 40,943	€ 40,943				€ 40,943
1	€ 1,627	€ 1,790	€ 439	€ 1,023	€ 328	
2	€ 1,502	€ 1,817	€ 446	€ 1,038	€ 333	
3	€ 1,386	€ 1,844	€ 452	€ 1,054	€ 338	
4	€ 1,279	€ 1,872	€ 459	€ 1,070	€ 343	
5	€ 1,180	€ 1,900	€ 466	€ 1,086	€ 348	
6	€ 1,089	€ 1,929	€ 473	€ 1,102	€ 353	
7	€ 1,004	€ 1,957	€ 480	€ 1,119	€ 359	
8	€ 927	€ 1,987	€ 487	€ 1,136	€ 364	
9	€ 855	€ 2,017	€ 495	€ 1,153	€ 369	
10	-€ 813	-€ 2,109	€ 502	€ 1,170	€ 375	-€ 4,156
TCO	€ 50,978					
TCO per km	€ 0.34					

TCO results (EUR/km)			
TCO - Capex	TCO - Fuel costs	TCO - O&M costs	TCO - Total
€ 0.26	€ 0.02	€ 0.06	€ 0.34

For the battery electric LCV, the cost of purchasing the vehicle currently accounts for 77% of the total TCO, followed by O&M costs at 17% and fuel costs at less than 6%.

TCO calculation – BEV LCV 2030

Assumptions	Input Data in real terms	Units
Initial purchase price (CAPEX)	34,953	EUR
Lifetime	10	years
Annual driving distance	15,000	km
Fuel price	0.09	EUR/kWh
Fuel economy	8.21	km/kWh
O&M (incl. all variable costs)	0.06	EUR/km
Insurance costs	369	EUR/year
Residual Value	10.00%	
Discount rate / cost of capital	10.00%	
CPI	1.5%	

Year	Discounted CF	Nominal CF	Fuel Costs	O&M	Insurance Costs	Residual Value
0	€ 34,953	€ 34,953				€ 34,953
1	€ 1,335	€ 1,469	€ 164	€ 930	€ 375	
2	€ 1,232	€ 1,491	€ 166	€ 944	€ 381	
3	€ 1,137	€ 1,513	€ 169	€ 958	€ 386	
4	€ 1,049	€ 1,536	€ 171	€ 973	€ 392	
5	€ 968	€ 1,559	€ 174	€ 987	€ 398	
6	€ 893	€ 1,582	€ 176	€ 1,002	€ 404	
7	€ 824	€ 1,606	€ 179	€ 1,017	€ 410	
8	€ 760	€ 1,630	€ 182	€ 1,032	€ 416	
9	€ 702	€ 1,655	€ 184	€ 1,048	€ 422	
10	-€ 720	-€ 1,868	€ 187	€ 1,063	€ 429	-€ 3,548
TCO	€ 43,133					
TCO per km	€ 0.29					

TCO results (EUR/km)			
TCO - Capex	TCO - Fuel costs	TCO - O&M costs	TCO - Total
€ 0.22	€ 0.01	€ 0.06	€ 0.29

For the battery electric LCV, in 2030 the cost of purchasing the vehicle accounts for almost 78% of the total TCO, followed by O&M costs at almost 20% and fuel costs at less than 3%.

TCO calculation – ICE LCV today

Assumptions	Input Data in real terms	Units
Initial purchase price (CAPEX)	34,617	EUR
Lifetime	10	years
Annual driving distance	15,000	km
Fuel price	1.29	EUR/Liter
Fuel economy	15.63	km/litre
O&M (incl. all variable costs)	0.05	EUR/km
Insurance costs	1,107	EUR/year
Residual Value	10.00%	
Discount rate / cost of capital	10.00%	
CPI	1.5%	

Year	Discounted CF	Nominal CF	Fuel Costs	O&M	Insurance Costs	Residual Value
0	€ 34,617	€ 34,617				€ 34,617
1	€ 2,830	€ 3,113	€ 1,258	€ 731	€ 1,124	
2	€ 2,611	€ 3,160	€ 1,277	€ 742	€ 1,141	
3	€ 2,409	€ 3,207	€ 1,296	€ 753	€ 1,158	
4	€ 2,223	€ 3,255	€ 1,315	€ 764	€ 1,175	
5	€ 2,051	€ 3,304	€ 1,335	€ 776	€ 1,193	
6	€ 1,893	€ 3,353	€ 1,355	€ 787	€ 1,211	
7	€ 1,747	€ 3,404	€ 1,375	€ 799	€ 1,229	
8	€ 1,612	€ 3,455	€ 1,396	€ 811	€ 1,248	
9	€ 1,487	€ 3,507	€ 1,417	€ 823	€ 1,266	
10	€ 18	€ 46	€ 1,438	€ 836	€ 1,285	-€ 3,514
TCO	€ 53,498					
TCO per km	€ 0.36					

TCO results (EUR/km)			
TCO - Capex	TCO - Fuel costs	TCO - O&M costs	TCO - Total
€ 0.22	€ 0.05	€ 0.08	€ 0.36

For the ICE LCV, the cost of purchasing the vehicle currently accounts for around 62% of the total TCO, followed by O&M costs at almost 23% and fuel costs at around 15%.

TCO calculation – ICE LCV 2030

Assumptions	Input Data in real terms	Units
Initial purchase price (CAPEX)	34,906	EUR
Lifetime	10	years
Annual driving distance	15,000	km
Fuel price	1.48	EUR/Liter
Fuel economy	21.72	km/litre
O&M (incl. all variable costs)	0.05	EUR/km
Insurance costs	436	EUR/year
Residual Value	10.00%	
Discount rate / cost of capital	10.00%	
CPI	1.5%	

Year	Discounted CF	Nominal CF	Fuel Costs	O&M	Insurance Costs	Residual Value
0	€ 34,906	€ 34,906				€ 34,906
1	€ 2,008	€ 2,208	€ 1,035	€ 731	€ 443	
2	€ 1,852	€ 2,241	€ 1,050	€ 742	€ 450	
3	€ 1,709	€ 2,275	€ 1,066	€ 753	€ 456	
4	€ 1,577	€ 2,309	€ 1,082	€ 764	€ 463	
5	€ 1,455	€ 2,344	€ 1,098	€ 776	€ 470	
6	€ 1,343	€ 2,379	€ 1,115	€ 787	€ 477	
7	€ 1,239	€ 2,415	€ 1,131	€ 799	€ 484	
8	€ 1,143	€ 2,451	€ 1,148	€ 811	€ 492	
9	€ 1,055	€ 2,488	€ 1,165	€ 823	€ 499	
10	-€ 392	-€ 1,018	€ 1,183	€ 836	€ 506	-€ 3,543
TCO	€ 47,896					
TCO per km	€ 0.32					

TCO results (EUR/km)			
TCO - Capex	TCO - Fuel costs	TCO - O&M costs	TCO - Total
€ 0.22	€ 0.04	€ 0.05	€ 0.32

For the ICE LCV, in 2030 the cost of purchasing the vehicle accounts for 70% of the total TCO, followed by O&M costs at just below 16% and fuel costs at around 14%.

TCO calculation – Fuel cell truck today

Assumptions	Input Data in real terms	Units
Initial purchase price (CAPEX)	312,949	EUR
Lifetime	10	years
Annual driving distance	140,000	km
Fuel price	7.00	EUR/kg
Fuel economy	11.76	km/kgH2
O&M (incl. all variable costs)	0.12	EUR/km
Insurance costs	1,878	EUR/year
Residual Value	10.00%	
Discount rate / cost of capital	10.00%	
CPI	1.5%	

Year	Discounted CF	Nominal CF	Fuel Costs	O&M	Insurance Costs	Residual Value
0	€ 312,949	€ 312,949				€ 312,949
1	€ 94,227	€ 103,649	€ 84,550	€ 17,194	€ 1,906	
2	€ 86,946	€ 105,204	€ 85,818	€ 17,452	€ 1,934	
3	€ 80,227	€ 106,782	€ 87,105	€ 17,714	€ 1,963	
4	€ 74,028	€ 108,384	€ 88,412	€ 17,979	€ 1,993	
5	€ 68,307	€ 110,010	€ 89,738	€ 18,249	€ 2,023	
6	€ 63,029	€ 111,660	€ 91,084	€ 18,523	€ 2,053	
7	€ 58,159	€ 113,335	€ 92,450	€ 18,801	€ 2,084	
8	€ 53,665	€ 115,035	€ 93,837	€ 19,083	€ 2,115	
9	€ 49,518	€ 116,760	€ 95,244	€ 19,369	€ 2,147	
10	€ 31,689	€ 82,193	€ 96,673	€ 19,660	€ 2,179	-€ 36,319
TCO	€ 972,742					
TCO per km	€ 0.69					

TCO results (EUR/km)			
TCO - Capex	TCO - Fuel costs	TCO - O&M costs	TCO - Total
€ 0.21	€ 0.39	€ 0.09	€ 0.69

In the case of the fuel cell truck, the costs for purchasing the truck currently account for slightly more than 30% of the total TCO. The largest share is accounted for by fuel costs at just under 57%, with O&M accounting for around 13%.

TCO calculation – Fuel cell truck 2030

Assumptions	Input Data in real terms	Units
Initial purchase price (CAPEX)	141,453	EUR
Lifetime	10	years
Annual driving distance	140,000	km
Fuel price	3.53	EUR/kg
Fuel economy	13.16	km/kgH2
O&M (incl. all variable costs)	0.11	EUR/km
Insurance costs	849	EUR/year
Residual Value	10.00%	
Discount rate / cost of capital	10.00%	
CPI	1.5%	

Year	Discounted CF	Nominal CF	Fuel Costs	O&M	Insurance Costs	Residual Value
0	€ 141,453	€ 141,453				€ 141,453
1	€ 49,667	€ 54,633	€ 38,141	€ 15,631	€ 861	
2	€ 45,829	€ 55,453	€ 38,713	€ 15,865	€ 874	
3	€ 42,287	€ 56,285	€ 39,294	€ 16,103	€ 887	
4	€ 39,020	€ 57,129	€ 39,883	€ 16,345	€ 901	
5	€ 36,005	€ 57,986	€ 40,481	€ 16,590	€ 914	
6	€ 33,222	€ 58,856	€ 41,089	€ 16,839	€ 928	
7	€ 30,655	€ 59,738	€ 41,705	€ 17,092	€ 942	
8	€ 28,286	€ 60,635	€ 42,331	€ 17,348	€ 956	
9	€ 26,101	€ 61,544	€ 42,965	€ 17,608	€ 970	
10	€ 17,755	€ 46,051	€ 43,610	€ 17,872	€ 985	-€ 16,416
TCO	€ 490,280					
TCO per km	€ 0.35					

TCO results (EUR/km)			
TCO - Capex	TCO - Fuel costs	TCO - O&M costs	TCO - Total
€ 0.10	€ 0.18	€ 0.08	€ 0.35

In the case of the fuel cell truck, the costs of purchasing the truck will account for almost 28% of the total TCO in 2030. The largest share is accounted for by fuel costs at just over 50%, with O&M accounting for around 22%.

TCO calculation – BEV truck today

Assumptions	Input Data in real terms	Units
Initial purchase price (CAPEX)	386,938	EUR
Lifetime	10	years
Annual driving distance	140,000	km
Fuel price	0.21	EUR/kWh
Fuel economy	0.74	km/kWh
O&M (incl. all variable costs)	0.11	EUR/km
Insurance costs	2,322	EUR/year
Residual Value	10.00%	
Discount rate / cost of capital	10.00%	
CPI	1.5%	

Year	Discounted CF	Nominal CF	Fuel Costs	O&M	Insurance Costs	Residual Value
0	€ 386,938	€ 386,938				€ 386,938
1	€ 52,278	€ 57,505	€ 39,518	€ 15,631	€ 2,356	
2	€ 48,238	€ 58,368	€ 40,111	€ 15,865	€ 2,392	
3	€ 44,511	€ 59,244	€ 40,712	€ 16,103	€ 2,428	
4	€ 41,071	€ 60,132	€ 41,323	€ 16,345	€ 2,464	
5	€ 37,897	€ 61,034	€ 41,943	€ 16,590	€ 2,501	
6	€ 34,969	€ 61,950	€ 42,572	€ 16,839	€ 2,539	
7	€ 32,267	€ 62,879	€ 43,211	€ 17,092	€ 2,577	
8	€ 29,774	€ 63,822	€ 43,859	€ 17,348	€ 2,615	
9	€ 27,473	€ 64,779	€ 44,517	€ 17,608	€ 2,655	
10	€ 10,208	€ 26,477	€ 45,184	€ 17,872	€ 2,694	-€ 39,274
TCO	€ 745,623					
TCO per km	€ 0.53					

TCO results (EUR/km)			
TCO - Capex	TCO - Fuel costs	TCO - O&M costs	TCO - Total
€ 0.27	€ 0.18	€ 0.08	€ 0.53

In the case of the battery electric truck, the acquisition costs of the vehicle currently account for about 50% of the total TCO, followed by fuel costs at just under 35% and O&M costs at just under 16%.

TCO calculation – BEV truck 2030

Assumptions	Input Data in real terms	Units
Initial purchase price (CAPEX)	260,071	EUR
Lifetime	10	years
Annual driving distance	140,000	km
Fuel price	0.09	EUR/kWh
Fuel economy	0.79	km/kWh
O&M (incl. all variable costs)	0.10	EUR/km
Insurance costs	1,560	EUR/year
Residual Value	10.00%	
Discount rate / cost of capital	10.00%	
CPI	1.5%	

Year	Discounted CF	Nominal CF	Fuel Costs	O&M	Insurance Costs	Residual Value
0	€ 260,071	€ 260,071				€ 260,071
1	€ 28,752	€ 31,627	€ 15,833	€ 14,210	€ 1,584	
2	€ 26,530	€ 32,102	€ 16,071	€ 14,423	€ 1,608	
3	€ 24,480	€ 32,583	€ 16,312	€ 14,639	€ 1,632	
4	€ 22,589	€ 33,072	€ 16,557	€ 14,859	€ 1,656	
5	€ 20,843	€ 33,568	€ 16,805	€ 15,082	€ 1,681	
6	€ 19,233	€ 34,072	€ 17,057	€ 15,308	€ 1,706	
7	€ 17,746	€ 34,583	€ 17,313	€ 15,538	€ 1,732	
8	€ 16,375	€ 35,101	€ 17,573	€ 15,771	€ 1,758	
9	€ 15,110	€ 35,628	€ 17,836	€ 16,007	€ 1,784	
10	€ 3,765	€ 9,765	€ 18,104	€ 16,248	€ 1,811	-€ 26,397
TCO	€ 455,494					
TCO per km	€ 0.33					

TCO results (EUR/km)			
TCO - Capex	TCO - Fuel costs	TCO - O&M costs	TCO - Total
€ 0.18	€ 0.07	€ 0.07	€ 0.33

In the case of the battery electric truck, the cost of purchasing the vehicle in 2030 will account for around 55% of the total TCO, while fuel costs and O&M costs will each account for just under 23%.

TCO calculation – ICE truck today

Assumptions	Input Data in real terms	Units
Initial purchase price (CAPEX)	87,000	EUR
Lifetime	10	years
Annual driving distance	140,000	km
Fuel price	1.23	EUR/Liter
Fuel economy	3.03	km/litre
O&M (incl. all variable costs)	0.13	EUR/km
Insurance costs	522	EUR/year
Residual Value	10.00%	
Discount rate / cost of capital	10.00%	
CPI	1.5%	

Year	Discounted CF	Nominal CF	Fuel Costs	O&M	Insurance Costs	Residual Value
0	€ 87,000	€ 87,000				€ 87,000
1	€ 70,139	€ 77,153	€ 57,866	€ 18,757	€ 530	
2	€ 64,719	€ 78,310	€ 58,734	€ 19,039	€ 538	
3	€ 59,718	€ 79,485	€ 59,615	€ 19,324	€ 546	
4	€ 55,104	€ 80,677	€ 60,509	€ 19,614	€ 554	
5	€ 50,846	€ 81,887	€ 61,417	€ 19,908	€ 562	
6	€ 46,917	€ 83,116	€ 62,338	€ 20,207	€ 571	
7	€ 43,291	€ 84,362	€ 63,273	€ 20,510	€ 579	
8	€ 39,946	€ 85,628	€ 64,222	€ 20,818	€ 588	
9	€ 36,859	€ 86,912	€ 65,186	€ 21,130	€ 597	
10	€ 30,607	€ 79,385	€ 66,163	€ 21,447	€ 606	-€ 8,831
TCO	€ 585,146					
TCO per km	€ 0.42					

TCO results (EUR/km)			
TCO - Capex	TCO - Fuel costs	TCO - O&M costs	TCO - Total
€ 0.06	€ 0.27	€ 0.09	€ 0.42

In the case of the diesel truck, the cost of purchasing the vehicle currently accounts for just over 14% of the total TCO. The largest share is accounted for by fuel costs at approximately 64% and O&M costs at around 21%.

TCO calculation – ICE truck 2030

Assumptions	Input Data in real terms	Units
Initial purchase price (CAPEX)	89,500	EUR
Lifetime	10	years
Annual driving distance	140,000	km
Fuel price	1.41	EUR/Liter
Fuel economy	3.28	km/litre
O&M (incl. all variable costs)	0.12	EUR/km
Insurance costs	537	EUR/year
Residual Value	10.00%	
Discount rate / cost of capital	10.00%	
CPI	1.5%	

Year	Discounted CF	Nominal CF	Fuel Costs	O&M	Insurance Costs	Residual Value
0	€ 89,500	€ 89,500				€ 89,500
1	€ 71,589	€ 78,748	€ 61,151	€ 17,052	€ 545	
2	€ 66,057	€ 79,929	€ 62,068	€ 17,308	€ 553	
3	€ 60,953	€ 81,128	€ 62,999	€ 17,567	€ 562	
4	€ 56,243	€ 82,345	€ 63,944	€ 17,831	€ 570	
5	€ 51,897	€ 83,580	€ 64,903	€ 18,098	€ 579	
6	€ 47,887	€ 84,834	€ 65,877	€ 18,370	€ 587	
7	€ 44,186	€ 86,107	€ 66,865	€ 18,645	€ 596	
8	€ 40,772	€ 87,398	€ 67,868	€ 18,925	€ 605	
9	€ 37,621	€ 88,709	€ 68,886	€ 19,209	€ 614	
10	€ 31,212	€ 80,955	€ 69,919	€ 19,497	€ 623	-€ 9,084
TCO	€ 597,917					
TCO per km	€ 0.43					

TCO results (EUR/km)			
TCO - Capex	TCO - Fuel costs	TCO - O&M costs	TCO - Total
€ 0.06	€ 0.28	€ 0.08	€ 0.43

In the case of the diesel truck, the costs of purchasing the vehicle in 2030 account for just over 14% of the total TCO. The largest share is accounted for by fuel costs at just under 67% and O&M costs at around 19%.

TCO calculation – Fuel cell bus today

Assumptions	Input Data in real terms	Units
Initial purchase price (CAPEX)	635,705	EUR
Lifetime	10	years
Annual driving distance	40,000	km
Fuel price	7.00	EUR/kg
Fuel economy	13.21	km/kgH2
O&M (incl. all variable costs)	0.18	EUR/km
Insurance costs	6,217	EUR/year
Residual Value	10.00%	
Discount rate / cost of capital	10.00%	
CPI	1.5%	

Year	Discounted CF	Nominal CF	Fuel Costs	O&M	Insurance Costs	Residual Value
0	€ 635,705	€ 635,705				€ 635,705
1	€ 31,790	€ 34,969	€ 21,507	€ 7,152	€ 6,310	
2	€ 29,334	€ 35,494	€ 21,830	€ 7,259	€ 6,405	
3	€ 27,067	€ 36,026	€ 22,157	€ 7,368	€ 6,501	
4	€ 24,976	€ 36,567	€ 22,489	€ 7,479	€ 6,599	
5	€ 23,046	€ 37,115	€ 22,827	€ 7,591	€ 6,698	
6	€ 21,265	€ 37,672	€ 23,169	€ 7,705	€ 6,798	
7	€ 19,622	€ 38,237	€ 23,517	€ 7,820	€ 6,900	
8	€ 18,105	€ 38,811	€ 23,869	€ 7,937	€ 7,004	
9	€ 16,706	€ 39,393	€ 24,228	€ 8,057	€ 7,109	
10	-€ 13,029	-€ 33,793	€ 24,591	€ 8,177	€ 7,215	-€ 73,776
TCO	€ 834,587					
TCO per km	€ 2.09					

TCO results (EUR/km)			
TCO - Capex	TCO - Fuel costs	TCO - O&M costs	TCO - Total
1.52	€ 0.35	€ 0.22	€ 2.09

In the case of the fuel cell bus, the cost of purchasing the vehicle currently accounts for around 73% of the total TCO, followed by fuel costs at 17% and O&M costs at just under 11%.

TCO calculation – Fuel cell bus 2030

Assumptions	Input Data in real terms	Units
Initial purchase price (CAPEX)	287,339	EUR
Lifetime	10	years
Annual driving distance	40,000	km
Fuel price	3.53	EUR/kg
Fuel economy	15.04	km/kgH2
O&M (incl. all variable costs)	0.16	EUR/km
Insurance costs	3,085	EUR/year
Residual Value	10.00%	
Discount rate / cost of capital	10.00%	
CPI	1.5%	

Year	Discounted CF	Nominal CF	Fuel Costs	O&M	Insurance Costs	Residual Value
0	€ 287,339	€ 287,339				€ 287,339
1	€ 17,426	€ 19,168	€ 9,535	€ 6,502	€ 3,131	
2	€ 16,079	€ 19,456	€ 9,678	€ 6,599	€ 3,178	
3	€ 14,837	€ 19,747	€ 9,823	€ 6,698	€ 3,226	
4	€ 13,690	€ 20,044	€ 9,971	€ 6,799	€ 3,274	
5	€ 12,632	€ 20,344	€ 10,120	€ 6,901	€ 3,323	
6	€ 11,656	€ 20,649	€ 10,272	€ 7,004	€ 3,373	
7	€ 10,755	€ 20,959	€ 10,426	€ 7,109	€ 3,424	
8	€ 9,924	€ 21,274	€ 10,583	€ 7,216	€ 3,475	
9	€ 9,157	€ 21,593	€ 10,741	€ 7,324	€ 3,527	
10	-€ 4,407	-€ 11,430	€ 10,902	€ 7,434	€ 3,580	-€ 33,347
TCO	€ 399,089					
TCO per km	€ 1.00					

TCO results (EUR/km)			
TCO - Capex	TCO - Fuel costs	TCO - O&M costs	TCO - Total
€ 0.69	€ 0.15	€ 0.16	€ 1.00

In the case of the fuel cell bus, the costs of purchasing the vehicle in 2030 account for around 69% of the total TCO, followed by the fuel costs and the O&M costs with just under 16% each.

TCO calculation – BEV bus today

Assumptions	Input Data in real terms	Units
Initial purchase price (CAPEX)	399,082	EUR
Lifetime	10	years
Annual driving distance	40,000	km
Fuel price	0.16	EUR/kWh
Fuel economy	0.58	km/kWh
O&M (incl. all variable costs)	0.18	EUR/km
Insurance costs	4,458	EUR/year
Residual Value	10.00%	
Discount rate / cost of capital	10.00%	
CPI	1.5%	

Year	Discounted CF	Nominal CF	Fuel Costs	O&M	Insurance Costs	Residual Value
0	€ 399,082	€ 399,082				€ 399,082
1	€ 20,905	€ 22,996	€ 11,212	€ 7,260	€ 4,524	
2	€ 19,290	€ 23,341	€ 11,380	€ 7,368	€ 4,592	
3	€ 17,799	€ 23,691	€ 11,551	€ 7,479	€ 4,661	
4	€ 16,424	€ 24,046	€ 11,724	€ 7,591	€ 4,731	
5	€ 15,155	€ 24,407	€ 11,900	€ 7,705	€ 4,802	
6	€ 13,984	€ 24,773	€ 12,078	€ 7,821	€ 4,874	
7	€ 12,903	€ 25,145	€ 12,260	€ 7,938	€ 4,947	
8	€ 11,906	€ 25,522	€ 12,443	€ 8,057	€ 5,021	
9	€ 10,986	€ 25,905	€ 12,630	€ 8,178	€ 5,097	
10	-€ 5,480	-€ 14,214	€ 12,820	€ 8,300	€ 5,173	-€ 40,507
TCO	€ 532,954					
TCO per km	€ 1.33					

TCO results (EUR/km)			
TCO - Capex	TCO - Fuel costs	TCO - O&M costs	TCO - Total
€ 0.96	€ 0.18	€ 0.19	€ 1.33

In the case of the battery electric bus, the costs of purchasing the vehicle currently account for around 72% of the total TCO, followed by the O&M costs with a good 14% and the fuel costs with just under 14%.

TCO calculation – BEV bus 2030

Assumptions	Input Data in real terms	Units
Initial purchase price (CAPEX)	268,233	EUR
Lifetime	10	years
Annual driving distance	40,000	km
Fuel price	0.09	EUR/kWh
Fuel economy	0.71	km/kWh
O&M (incl. all variable costs)	0.16	EUR/km
Insurance costs	2,212	EUR/year
Residual Value	10.00%	
Discount rate / cost of capital	10.00%	
CPI	1.5%	

Year	Discounted CF	Nominal CF	Fuel Costs	O&M	Insurance Costs	Residual Value
0	€ 268,233	€ 268,233				€ 268,233
1	€ 12,642	€ 13,907	€ 5,062	€ 6,600	€ 2,245	
2	€ 11,665	€ 14,115	€ 5,138	€ 6,699	€ 2,279	
3	€ 10,764	€ 14,327	€ 5,215	€ 6,799	€ 2,313	
4	€ 9,932	€ 14,542	€ 5,293	€ 6,901	€ 2,347	
5	€ 9,165	€ 14,760	€ 5,373	€ 7,005	€ 2,383	
6	€ 8,457	€ 14,981	€ 5,453	€ 7,110	€ 2,418	
7	€ 7,803	€ 15,206	€ 5,535	€ 7,216	€ 2,455	
8	€ 7,200	€ 15,434	€ 5,618	€ 7,324	€ 2,492	
9	€ 6,644	€ 15,666	€ 5,702	€ 7,434	€ 2,529	
10	-€ 4,366	-€ 11,325	€ 5,788	€ 7,546	€ 2,567	-€ 27,226
TCO	€ 348,140					
TCO per km	€ 0.87					

TCO results (EUR/km)			
TCO - Capex	TCO - Fuel costs	TCO - O&M costs	TCO - Total
€ 0.64	€ 0.08	€ 0.14	€ 0.87

For the battery electric bus, the cost of purchasing the vehicle in 2030 accounts for around 74% of the total TCO, followed by O&M costs at just under 17% and fuel costs at less than 10%.

TCO calculation – ICE bus today

Assumptions	Input Data in real terms	Units
Initial purchase price (CAPEX)	284,302	EUR
Lifetime	10	years
Annual driving distance	40,000	km
Fuel price	1.23	EUR/Liter
Fuel economy	2.58	km/litre
O&M (incl. all variable costs)	0.22	EUR/km
Insurance costs	2,929	EUR/year
Residual Value	10.00%	
Discount rate / cost of capital	10.00%	
CPI	1.5%	

Year	Discounted CF	Nominal CF	Fuel Costs	O&M	Insurance Costs	Residual Value
0	€ 284,302	€ 284,302				€ 284,302
1	€ 28,542	€ 31,396	€ 19,445	€ 8,978	€ 2,973	
2	€ 26,336	€ 31,867	€ 19,737	€ 9,113	€ 3,017	
3	€ 24,301	€ 32,345	€ 20,033	€ 9,249	€ 3,062	
4	€ 22,424	€ 32,830	€ 20,334	€ 9,388	€ 3,108	
5	€ 20,691	€ 33,323	€ 20,639	€ 9,529	€ 3,155	
6	€ 19,092	€ 33,823	€ 20,948	€ 9,672	€ 3,202	
7	€ 17,617	€ 34,330	€ 21,262	€ 9,817	€ 3,250	
8	€ 16,255	€ 34,845	€ 21,581	€ 9,964	€ 3,299	
9	€ 14,999	€ 35,368	€ 21,905	€ 10,114	€ 3,349	
10	€ 2,715	€ 7,041	€ 22,234	€ 10,265	€ 3,399	-€ 28,857
TCO	€ 477,274					
TCO per km	€ 1.19					

TCO results (EUR/km)			
TCO - Capex	TCO - Fuel costs	TCO - O&M costs	TCO - Total
€ 0.68	€ 0.32	€ 0.19	€ 1.19

In the case of the diesel bus, the cost of purchasing the vehicle currently accounts for around 57% of the total TCO, followed by fuel costs at just under 27% and O&M costs at approximately 16%.

TCO calculation – ICE bus 2030

Assumptions	Input Data in real terms	Units
Initial purchase price (CAPEX)	292,471	EUR
Lifetime	10	years
Annual driving distance	40,000	km
Fuel price	1.41	EUR/Liter
Fuel economy	2.78	km/litre
O&M (incl. all variable costs)	0.18	EUR/km
Insurance costs	3,450	EUR/year
Residual Value	10.00%	
Discount rate / cost of capital	10.00%	
CPI	1.5%	

Year	Discounted CF	Nominal CF	Fuel Costs	O&M	Insurance Costs	Residual Value
0	€ 292,471	€ 292,471				€ 292,471
1	€ 28,556	€ 31,411	€ 20,602	€ 7,308	€ 3,502	
2	€ 26,349	€ 31,883	€ 20,911	€ 7,418	€ 3,554	
3	€ 24,313	€ 32,361	€ 21,225	€ 7,529	€ 3,607	
4	€ 22,434	€ 32,846	€ 21,543	€ 7,642	€ 3,662	
5	€ 20,701	€ 33,339	€ 21,866	€ 7,756	€ 3,716	
6	€ 19,101	€ 33,839	€ 22,194	€ 7,873	€ 3,772	
7	€ 17,625	€ 34,347	€ 22,527	€ 7,991	€ 3,829	
8	€ 16,263	€ 34,862	€ 22,865	€ 8,111	€ 3,886	
9	€ 15,007	€ 35,385	€ 23,208	€ 8,232	€ 3,945	
10	€ 2,402	€ 6,230	€ 23,556	€ 8,356	€ 4,004	-€ 29,686
TCO	€ 485,223					
TCO per km	€ 1.21					

TCO results (EUR/km)			
TCO - Capex	TCO - Fuel costs	TCO - O&M costs	TCO - Total
€ 0.70	€ 0.33	€ 0.18	€ 1.21

In the case of the diesel bus, the costs of purchasing the vehicle in 2030 account for around 58% of the total TCO, followed by fuel costs at just under 28% and O&M costs at around 15%.

Appendix – part B

Part B of the appendix deals with the results of the GREET® model in detail.

The following is a breakdown of the individual results of the GREET® model calculations for all vehicle technologies in the 4 vehicle segments analysed in this master's thesis.

GREET® model 2021: total energy use & CO_2 emissions output data – Fuel cell LDV

Fuel cell - LDV	Total Energy (MJ/hkm)						CO_2 (g/km)					
	2019	2030	2035	2040	2045	2050	2019	2030	2035	2040	2045	2050
WTP	**52.8**	**36.5**	**30.8**	**27.7**	**27.7**	**27.7**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Mode - regular	135.7	104.0	87.6	78.9	78.9	78.9	0.00	0.00	0.00	0.00	0.00	0.00
Operation Only	135.7	104.0	87.6	78.9	78.9	78.9	0.00	0.00	0.00	0.00	0.00	0.00
WTW	**188.5**	**140.6**	**118.4**	**106.6**	**106.6**	**106.6**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Components - Powertrain System	6.5	5.0	4.9	4.8	4.8	4.8	3.26	2.38	2.30	2.25	2.23	2.22
Components - Transmission System/Gearbox	1.3	1.0	1.0	1.0	1.0	1.0	0.82	0.63	0.61	0.61	0.61	0.61
Components - Chassis (w/o battery)	7.2	5.7	5.6	5.6	5.5	5.5	5.10	3.90	3.80	3.79	3.77	3.75
Components - Traction Motor (HEV, PHEV, EV, FCV)	1.5	1.2	1.2	1.2	1.2	1.2	0.97	0.75	0.73	0.72	0.72	0.72
Components - Electronic Controller (HEV, PHEV, EV, FCV)	1.7	1.3	1.3	1.3	1.3	1.3	0.80	0.62	0.61	0.61	0.60	0.60
Components - Fuel Cell Onboard Storage (FCV)	23.1	22.4	22.1	22.1	22.0	21.9	10.70	9.42	9.10	8.96	8.82	8.72
Components - Vehicle Body	19.7	14.8	14.4	14.5	14.4	14.4	11.34	8.30	8.04	8.02	7.98	7.95
Components - Vehicle Tire Replacement	2.9	2.8	2.8	2.8	2.8	2.8	1.99	1.94	1.92	1.92	1.91	1.91
Components	63.9	54.2	53.3	53.1	53.0	52.9	34.96	27.93	27.12	26.87	26.63	26.47
ADR - Vehicle (Assembly, Disposal, and Recycling)	18.0	17.3	17.0	17.0	16.9	16.8	10.44	9.26	8.96	8.83	8.70	8.59
ADR	18.0	17.3	17.0	17.0	16.9	16.8	10.44	9.26	8.96	8.83	8.70	8.59
Fluids - Brake Fluid	0.1	0.1	0.1	0.1	0.1	0.1	0.07	0.07	0.07	0.07	0.07	0.07
Fluids - Transmission Fluid	0.1	0.1	0.1	0.1	0.1	0.1	0.03	0.03	0.03	0.03	0.03	0.03
Fluids - Engine/Powertrain Coolant	0.4	0.4	0.4	0.4	0.4	0.4	0.09	0.09	0.08	0.08	0.08	0.08
Fluids - Windshield Fluid	0.5	0.5	0.5	0.5	0.5	0.5	0.06	0.05	0.05	0.05	0.05	0.05
Fluids - Adhesives	0.7	0.7	0.7	0.7	0.7	0.7	0.24	0.22	0.22	0.22	0.22	0.22
Fluids	1.7	1.7	1.7	1.7	1.7	1.7	0.48	0.46	0.45	0.45	0.45	0.45
Battery - Lead-Acid (Vehicle Battery Assembly)	0.3	0.3	0.3	0.3	0.3	0.3	0.12	0.11	0.11	0.11	0.11	0.11
Battery - Ni-MH (Vehicle Battery Assembly)	2.8	2.4	2.4	2.3	2.3	2.3	1.55	1.27	1.25	1.19	1.18	1.17
Battery	3.1	2.7	2.7	2.5	2.5	2.5	1.67	1.38	1.36	1.29	1.29	1.28
Others	0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00	0.00	0.00
Total	**275.1**	**216.4**	**193.1**	**180.9**	**180.7**	**180.5**	**47.55**	**39.02**	**37.89**	**37.44**	**37.06**	**36.79**

MJ stands for megajoule; by converting the energy consumption of the different energy sources into joules per meter, vehicles can be compared regardless of the energy source. (Väljaots 2017: 32), hkm is hundred kilometres

A fuel cell vehicle does not produce any CO_2 emissions at the point of use (pump-to-wheel), but it does produce CO_2 emissions in connection with the manufacturing of the vehicle. This concerns i) raw material required for the vehicle, ii) processing of the vehicle material, iii) manufacturing and assembly of the vehicle, iv) and the end-of-life decommissioning and recycling of the vehicle.

In 2019, the GREET model calculates that a fuel cell LDV produces just under 48 g/km of CO_2. Almost 70% of the CO_2 emissions come from "Components - Fuel Cell Onboard Storage", "Components -Vehicle Body" and "Assembly, Disposal, and Recycling". From 2019 to 2050, the GREET model calculates a reduction in total CO_2 emissions of around 23% to just under 37 g/km. Total energy consumption will fall by almost 50% to approximately 28 MJ/hkm in this period.

GREET® model 2021: total energy use & CO_2 emissions output data – Fuel cell LCV

Fuel cell - LCV	Total Energy (MJ/hkm)						CO_2 (g/km)					
	2019	2030	2035	2040	2045	2050	2019	2030	2035	2040	2045	2050
WTP	**71.9**	**42.0**	**41.7**	**38.2**	**38.2**	**38.2**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Mode - regular	185.0	119.6	118.8	108.7	108.7	108.7	0.00	0.00	0.00	0.00	0.00	0.00
Operation Only	185.0	119.6	118.8	108.7	108.7	108.7	0.00	0.00	0.00	0.00	0.00	0.00
WTW	**256.9**	**161.7**	**160.6**	**146.9**	**146.9**	**146.9**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Components - Powertrain System	7.3	5.6	5.6	5.3	5.3	5.3	3.64	2.68	2.65	2.47	2.45	2.43
Components - Transmission System/Gearbox	1.5	1.1	1.0	1.0	1.0	1.0	0.98	0.68	0.65	0.63	0.63	0.62
Components - Chassis (w/o battery)	12.0	8.5	8.2	7.9	7.9	7.9	8.26	5.69	5.50	5.29	5.27	5.25
Components - Traction Motor (HEV, PHEV, EV, FCV)	1.9	1.3	1.3	1.2	1.2	1.2	1.20	0.82	0.79	0.76	0.76	0.75
Components - Electronic Controller (HEV, PHEV, EV, FCV)	2.1	1.5	1.4	1.4	1.4	1.4	0.99	0.69	0.67	0.64	0.64	0.64
Components - Fuel Cell Onboard Storage (FCV)	27.5	26.6	26.3	26.2	26.1	26.0	12.70	11.18	10.81	10.64	10.47	10.35
Components - Vehicle Body	19.6	12.3	11.8	11.3	11.3	11.2	11.25	6.86	6.52	6.23	6.20	6.18
Components - Vehicle Tire Replacement	5.4	5.4	5.4	5.3	5.3	5.3	3.75	3.66	3.63	3.62	3.61	3.61
Components	77.2	62.2	61.0	59.6	59.5	59.4	42.76	32.24	31.22	30.27	30.00	29.83
ADR - Vehicle (Assembly, Disposal, and Recycling)	32.7	31.4	30.9	30.8	30.7	30.5	19.02	16.79	16.24	15.99	15.74	15.55
ADR	32.7	31.4	30.9	30.8	30.7	30.5	19.02	16.79	16.24	15.99	15.74	15.55
Fluids - Brake Fluid	0.1	0.1	0.1	0.1	0.1	0.1	0.08	0.08	0.08	0.08	0.08	0.08
Fluids - Transmission Fluid	0.1	0.1	0.1	0.1	0.1	0.1	0.04	0.04	0.04	0.04	0.04	0.04
Fluids - Engine/Powertrain Coolant	0.6	0.6	0.6	0.6	0.6	0.6	0.13	0.13	0.13	0.13	0.13	0.13
Fluids - Windshield Fluid	0.9	0.9	0.9	0.9	0.9	0.9	0.11	0.10	0.10	0.10	0.10	0.10
Fluids - Adhesives	0.9	0.8	0.8	0.8	0.8	0.8	0.30	0.28	0.28	0.28	0.28	0.27
Fluids	2.5	2.5	2.5	2.5	2.5	2.5	0.65	0.62	0.62	0.62	0.61	0.61
Battery - Lead-Acid (Vehicle Battery Assembly)	0.4	0.4	0.4	0.4	0.4	0.4	0.18	0.17	0.17	0.17	0.17	0.17
Battery - Ni-MH (Vehicle Battery Assembly)	3.2	2.5	2.5	2.1	2.1	2.1	1.73	1.32	1.30	1.12	1.11	1.11
Battery	3.6	2.9	2.9	2.6	2.6	2.6	1.92	1.49	1.47	1.29	1.28	1.27
Total	**372.9**	**260.6**	**257.9**	**242.4**	**242.1**	**241.9**	**64.35**	**51.15**	**49.55**	**48.17**	**47.63**	**47.25**

In 2019, the GREET® model calculates that a fuel cell LCV emits approximately 64 g/km of CO_2. About two thirds of the CO_2 emissions come from "Components - Fuel Cell Onboard Storage", "Components - Vehicle Body" and "Assembly, Disposal, and Recycling", with the last item accounting for almost 30% of the total CO_2 emissions. From 2019 to 2050, the GREET® model calculates a reduction in total CO_2 emissions of almost 27% to approx. 47 g/km. Total energy consumption falls by almost 47% to 38 MJ/hkm in this period.

GREET® model 2021: total energy use & CO_2 emissions output data – Fuel cell MCV

Fuel cell - MCV	Total Energy (MJ/hkm)						CO_2 (g/km)					
	2019	2030	2035	2040	2045	2050	2019	2030	2035	2040	2045	2050
WTP	**216.1**	**141.4**	**130.0**	**130.0**	**130.0**	**114.7**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Mode - Regular	555.7	402.5	370.0	370.0	370.0	326.6	0.00	0.00	0.00	0.00	0.00	0.00
Operation Only	555.7	402.5	370.0	370.0	370.0	326.6	0.00	0.00	0.00	0.00	0.00	0.00
WTW	**771.8**	**543.9**	**500.0**	**500.0**	**500.0**	**441.3**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Components - Powertrain System	1.9	1.9	1.9	1.9	1.9	1.9	0.91	0.85	0.84	0.83	0.82	0.82
Components - Transmission System/Gearbox	0.4	0.4	0.4	0.4	0.4	0.4	0.23	0.22	0.22	0.22	0.22	0.22
Components - Chassis (w/o battery)	13.5	13.3	13.3	13.2	13.2	13.2	9.62	9.27	9.18	9.14	9.10	9.08
Components - Traction Motor (HEV, PHEV, EV, FCV)	0.7	0.7	0.6	0.6	0.6	0.6	0.42	0.41	0.40	0.40	0.40	0.40
Components - Electronic Controller (HEV, PHEV, EV, FCV)	0.1	0.1	0.1	0.1	0.1	0.1	0.04	0.04	0.04	0.04	0.04	0.04
Components - Fuel Cell Onboard Storage (FCV)	7.9	7.7	7.6	7.6	7.5	7.5	3.57	3.16	3.06	3.01	2.97	2.94
Components - Van/Box	16.2	16.2	16.2	16.2	16.2	16.2	8.79	8.77	8.74	8.72	8.71	8.70
Components - Vehicle Body	7.6	7.5	7.4	7.4	7.4	7.4	4.08	3.91	3.87	3.85	3.83	3.81
Components - Lift-gates	2.1	2.1	2.0	2.0	2.0	2.0	1.70	1.63	1.61	1.60	1.59	1.59
Components	50.3	49.7	49.5	49.4	49.3	49.3	29.36	28.26	27.95	27.81	27.67	27.58
ADR - Vehicle (Assembly, Disposal, and Recycling)	39.2	37.2	36.5	36.3	36.1	35.9	23.07	19.59	18.74	18.35	17.95	17.65
ADR	39.2	37.2	36.5	36.3	36.1	35.9	23.07	19.59	18.74	18.35	17.95	17.65
Fluids - Steer Axle Lubricant	0.6	0.6	0.6	0.6	0.6	0.6	0.33	0.32	0.32	0.32	0.32	0.32
Fluids - Drive Axle Lubricant	0.0	0.0	0.0	0.0	0.0	0.0	0.02	0.02	0.02	0.02	0.02	0.02
Fluids - Inter-axle/Drive-shaft Lubricant	1.1	1.1	1.1	1.1	1.1	1.1	0.65	0.65	0.65	0.64	0.64	0.65
Fluids - Wheel-end Lubricant: Steer Axle	0.1	0.1	0.1	0.1	0.1	0.1	0.03	0.03	0.03	0.03	0.03	0.03
Fluids - Wheel-end Lubricant: Drive Axle	0.1	0.1	0.1	0.1	0.1	0.1	0.03	0.03	0.03	0.03	0.03	0.03
Fluids - Transmission Fluid	0.1	0.1	0.1	0.1	0.1	0.1	0.04	0.04	0.04	0.04	0.04	0.04
Fluids - Engine/Powertrain Coolant	0.1	0.1	0.1	0.1	0.1	0.1	0.02	0.02	0.02	0.02	0.02	0.02
Fluids - Coolant Cleaner	0.2	0.2	0.2	0.2	0.2	0.2	0.13	0.13	0.13	0.13	0.13	0.13
Fluids - Windshield Fluid	0.7	0.7	0.7	0.7	0.7	0.7	0.09	0.08	0.08	0.08	0.08	0.08
Fluids - Adhesives	0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00	0.00	0.00
Fluids	2.9	2.9	2.9	2.9	2.9	2.9	1.34	1.33	1.32	1.32	1.32	1.33
Battery - Lead-Acid (Vehicle Battery Assembly)	0.4	0.4	0.4	0.4	0.4	0.4	0.19	0.18	0.17	0.17	0.17	0.17
Battery - Lithium-ion Battery Bill-of-material	1.0	1.0	1.0	1.0	1.0	1.0	0.60	0.57	0.56	0.56	0.56	0.55
Battery - Lithium Ion (Vehicle Battery Assembling Part)	0.2	0.2	0.2	0.2	0.2	0.2	0.09	0.09	0.09	0.09	0.08	0.08
Battery	1.6	1.6	1.6	1.6	1.6	1.6	0.88	0.84	0.82	0.82	0.81	0.81
Total	**865.8**	**635.3**	**590.5**	**590.2**	**589.8**	**530.9**	**54.65**	**50.01**	**48.84**	**48.29**	**47.75**	**47.36**

In 2019, the GREET® model calculates that a fuel cell MCV produces about 55 g/km of CO_2, with "Assembly, Disposal, and Recycling" accounting for more than 40% of total CO_2 emissions. The item "Components - Chassis" accounts for almost 18% and "Components - Van/Box" for 16%. From 2019 to 2050, the GREET® model calculates a reduction in total CO_2 emissions of a good 13% to approx. 47 g/km. Total energy consumption falls by almost 47% to 115 MJ/hkm in this period.

GREET® model 2021: total energy use & CO_2 emissions output data – Fuel cell HCV

Fuel cell - HCV	Total Energy (MJ/hkm)						CO_2 (g/km)					
	2019	2030	2035	2040	2045	2050	2019	2030	2035	2040	2045	2050
WTP	**481.6**	**272.4**	**238.1**	**238.1**	**238.1**	**203.1**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Mode - Regular	1,238.4	775.4	677.7	677.7	677.7	578.1	0.00	0.00	0.00	0.00	0.00	0.00
Operation Only	1,238.4	775.4	677.7	677.7	677.7	578.1	0.00	0.00	0.00	0.00	0.00	0.00
WTW	**1,720.0**	**1,047.8**	**915.9**	**915.9**	**915.9**	**781.2**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Components - Vehicle Body	5.2	5.2	5.2	5.2	5.1	5.1	2.75	2.64	2.61	2.60	2.59	2.58
Components - Powertrain System	2.4	2.4	2.3	2.3	2.3	2.3	1.13	1.05	1.03	1.02	1.01	1.01
Components - Transmission System/Gearbox	0.4	0.4	0.4	0.4	0.4	0.4	0.26	0.25	0.24	0.24	0.24	0.24
Components - Chassis (w/o battery)	15.0	14.8	14.7	14.7	14.7	14.7	10.67	10.31	10.22	10.18	10.14	10.11
Components - Traction Motor (HEV, PHEV, EV, FCV)	0.7	0.7	0.7	0.7	0.7	0.7	0.46	0.44	0.44	0.43	0.43	0.43
Components - Electronic Controller (HEV, PHEV, EV, FCV)	0.1	0.1	0.1	0.1	0.1	0.1	0.05	0.05	0.04	0.04	0.04	0.04
Components - Fuel Cell Onboard Storage (FCV)	27.8	26.9	26.6	26.6	26.5	26.4	12.60	11.12	10.75	10.59	10.42	10.31
Components	51.7	50.4	50.0	49.9	49.8	49.7	27.91	25.85	25.34	25.11	24.87	24.72
ADR - Vehicle (Assembly, Disposal, and Recycling)	61.3	58.1	57.1	56.7	56.4	56.0	36.10	30.61	29.26	28.63	28.01	27.53
ADR	61.3	58.1	57.1	56.7	56.4	56.0	36.10	30.61	29.26	28.63	28.01	27.53
Fluids - Steer Axle Lubricant	0.9	0.9	0.9	0.9	0.9	0.9	0.54	0.54	0.54	0.54	0.54	0.54
Fluids - Drive Axle Lubricant	0.1	0.1	0.1	0.1	0.1	0.1	0.08	0.08	0.08	0.08	0.08	0.08
Fluids - Inter-axle/Drive-shaft Lubricant	0.4	0.4	0.4	0.4	0.4	0.4	0.22	0.22	0.22	0.22	0.22	0.22
Fluids - Wheel-end Lubricant: Steer Axle	0.1	0.1	0.1	0.1	0.1	0.1	0.03	0.03	0.03	0.03	0.03	0.03
Fluids - Wheel-end Lubricant: Drive Axle	0.1	0.1	0.1	0.1	0.1	0.1	0.07	0.07	0.07	0.07	0.07	0.07
Fluids - Transmission Fluid	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-	-	-
Fluids - Engine/Powertrain Coolant	0.1	0.1	0.1	0.1	0.1	0.1	0.03	0.02	0.02	0.02	0.02	0.02
Fluids - Coolant Cleaner	0.1	0.1	0.1	0.1	0.1	0.1	0.07	0.07	0.07	0.07	0.07	0.07
Fluids - Windshield Fluid	0.1	0.1	0.1	0.1	0.1	0.1	0.01	0.01	0.01	0.01	0.01	0.01
Fluids	2.0	1.9	1.9	1.9	1.9	1.9	1.05	1.04	1.04	1.04	1.04	1.04
Battery - Lead-Acid (Vehicle Battery Assembly)	0.1	0.1	0.1	0.1	0.1	0.1	0.03	0.03	0.03	0.02	0.02	0.02
Battery - Lithium-ion Battery Bill-of-material	1.4	1.4	1.4	1.4	1.4	1.4	0.84	0.80	0.79	0.79	0.78	0.78
Battery - Lithium Ion (Vehicle Battery Assembling Part)	0.2	0.2	0.2	0.2	0.2	0.2	0.14	0.13	0.13	0.13	0.13	0.13
Battery	1.7	1.7	1.7	1.7	1.7	1.7	1.00	0.96	0.94	0.94	0.93	0.93
Others - Trailer Body	10.8	10.9	10.9	10.9	10.9	10.9	5.87	5.87	5.85	5.84	5.83	5.82
Others - Trailer Chassis	16.9	16.7	16.7	16.6	16.6	16.6	11.57	11.25	11.16	11.13	11.09	11.07
Others - Trailer Auxiliary	0.8	0.8	0.8	0.8	0.8	0.8	0.53	0.51	0.50	0.50	0.50	0.49
Others - Vehicle (Assembly, Disposal, and Recycling)	1.4	1.4	1.3	1.3	1.3	1.3	0.84	0.72	0.69	0.68	0.67	0.65
Others - Drive Axle Lubricant	0.1	0.1	0.1	0.1	0.1	0.1	0.08	0.08	0.08	0.08	0.08	0.08
Others - Wheel-end Lubricant: Drive Axle	0.1	0.1	0.1	0.1	0.1	0.1	0.07	0.07	0.07	0.07	0.07	0.07
Others	30.3	30.0	29.9	29.9	29.9	29.9	18.96	18.48	18.35	18.28	18.22	18.18
Total	**1,866.9**	**1,190.0**	**1,056.5**	**1,056.0**	**1,055.5**	**920.4**	**85.02**	**76.94**	**74.92**	**74.00**	**73.07**	**72.40**

In 2019, the GREET® model calculates that a fuel cell HCV produces CO_2 of around 85 g/km, with "Assembly, Disposal, and Recycling" responsible for around 42% of the total CO_2 emissions. The item "Components - Fuel Cell Onboard Storage" accounts for just under 15% and "Components - Chassis" for just under 13%. From 2019 to 2050, the GREET® model calculates a reduction in total CO_2 emissions of just under 15% to approx. 72 g/km. Total energy consumption falls by more than half in this period, namely by almost 58% to 203 MJ/hkm.

GREET® model 2021: total energy use & CO_2 emissions output data – Fuel cell bus

Fuel cell bus	Total Energy (MJ/hkm)						CO_2 (g/km)					
	2019	2030	2035	2040	2045	2050	2019	2030	2035	2040	2045	2050
WTP	**310.1**	**167.2**	**155.5**	**155.5**	**155.5**	**135.9**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Mode - Regular	797.3	475.8	442.5	442.5	442.5	386.8	0.00	0.00	0.00	0.00	0.00	0.00
Operation Only	797.3	475.8	442.5	442.5	442.5	386.8	0.00	0.00	0.00	0.00	0.00	0.00
WTW	**1,107.4**	**643.0**	**597.9**	**597.9**	**597.9**	**522.7**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
ADR - Vehicle (Assembly, Disposal, and Recycling)	86.8	82.3	80.8	80.3	79.8	79.4	51.04	43.36	41.47	40.60	39.73	39.06
ADR	86.8	82.3	80.8	80.3	79.8	79.4	51.04	43.36	41.47	40.60	39.73	39.06
Total	**1,194.1**	**725.3**	**678.8**	**678.3**	**677.8**	**602.1**	**51.04**	**43.36**	**41.47**	**40.60**	**39.73**	**39.06**

In 2019, the GREET® model calculates that for a fuel cell bus, the item "Assembly, Disposal, and Recycling" emits around 51 g/km of CO_2. From 2019 to 2050, this value drops by around 23% to 39 g/km. Total energy consumption falls by more than half in this period, namely by 56% to 136 MJ/hkm.

GREET® model 2021: total energy use & CO_2 emissions output data - LDV Otto

LDV - Otto	Total Energy (MJ/hkm)						CO_2 (g/km)					
	2019	2030	2035	2040	2045	2050	2019	2030	2035	2040	2045	2050
WTP	**67.0**	**53.5**	**47.3**	**43.7**	**43.7**	**44.4**	**42.72**	**33.96**	**29.94**	**27.64**	**27.57**	**27.92**
Mode - regular	245.2	203.1	180.5	167.1	167.1	167.1	175.22	146.17	129.75	119.97	119.97	119.97
Operation Only	245.2	203.1	180.5	167.1	167.1	167.1	175.22	146.17	129.75	119.97	119.97	119.97
WTW	**312.3**	**256.6**	**227.8**	**210.8**	**210.8**	**211.5**	**217.94**	**180.13**	**159.69**	**147.61**	**147.54**	**147.88**
ADR - Vehicle (Assembly, Disposal, and Recycling)	12.3	11.8	11.7	11.6	11.6	11.5	7.15	6.33	6.13	6.04	5.95	5.88
ADR	12.3	11.8	11.7	11.6	11.6	11.5	7.15	6.33	6.13	6.04	5.95	5.88
Total	**324.6**	**268.4**	**239.5**	**222.4**	**222.3**	**223.0**	**225.09**	**186.46**	**165.83**	**153.65**	**153.49**	**153.76**

In contrast to a fuel cell electric vehicle or a BEV, an ICE vehicle also produces CO_2 emissions at the point of use. These also represent by far the largest part of the total CO_2 emissions.

For an LDV with a gasoline engine, the GREET® model calculates CO_2 emissions of 225 g/km for 2019. Almost 19% of these emissions are attributable to the well-to-pump section, which includes the CO_2 emissions produced during crude oil production, processing, and transportation of the fuel. Around 78% of the total CO_2 emissions are caused by the operation of the ICE LDV. For the period 2019 to 2050, the GREET® model calculates a reduction in CO_2 emissions of 32% to 154 g/km. Total energy consumption falls by approximately 34% to 44 MJ/hkm in this period.

GREET® model 2021: total energy use & CO_2 emissions output data - LDV Diesel

LDV - Diesel	Total Energy (MJ/hkm)						CO_2 (g/km)					
	2019	2030	2035	2040	2045	2050	2019	2030	2035	2040	2045	2050
WTP	**43.3**	**38.5**	**33.3**	**31.6**	**31.6**	**32.4**	**28.94**	**25.63**	**22.10**	**20.98**	**20.92**	**21.34**
Mode - regular	235.0	216.5	188.5	179.5	179.5	179.5	172.40	160.93	139.94	133.21	133.21	133.21
Operation Only	235.0	216.5	188.5	179.5	179.5	179.5	172.40	160.93	139.94	133.21	133.21	133.21
WTW	**278.3**	**255.0**	**221.7**	**211.1**	**211.1**	**211.9**	**201.34**	**186.55**	**162.04**	**154.19**	**154.13**	**154.54**
ADR - Vehicle (Assembly, Disposal, and Recycling)	12.3	11.8	11.7	11.6	11.6	11.5	7.15	6.33	6.13	6.04	5.95	5.88
ADR	12.3	11.8	11.7	11.6	11.6	11.5	7.15	6.33	6.13	6.04	5.95	5.88
Total	**290.6**	**266.8**	**233.4**	**222.7**	**222.6**	**223.4**	**208.48**	**192.89**	**168.18**	**160.23**	**160.08**	**160.42**

For a diesel-powered LDV, the GREET® model calculates CO_2 emissions of 208 g/km for 2019. Almost 14% of these emissions are attributable to the well-to-pump section. The operation of the ICE diesel accounts for around 83% of the total CO_2

emissions. For the period 2019 to 2050, the GREET® model calculates a decrease in CO_2 emissions of 23% to 160 g/km. Total energy consumption falls by approximately 25% to 32 MJ/hkm in this period.

GREET® model 2021: total energy use & CO_2 emissions output data – LCV Gasoline E10

LCV - Gasoline E10	Total Energy (MJ/hkm)						CO_2 (g/km)					
	2019	2030	2035	2040	2045	2050	2019	2030	2035	2040	2045	2050
WTP	**92.1**	**74.6**	**66.8**	**60.9**	**60.8**	**61.7**	**58.74**	**46.95**	**41.92**	**38.07**	**37.97**	**38.40**
Mode - Regular (E10)	345.2	286.3	258.1	235.4	235.4	235.4	244.52	203.05	182.57	166.11	166.05	166.03
Operation Only	345.2	286.3	258.1	235.4	235.4	235.4	244.52	203.05	182.57	166.11	166.05	166.03
WTW	**437.3**	**360.9**	**324.9**	**296.3**	**296.2**	**297.1**	**303.26**	**250.00**	**224.49**	**204.18**	**204.02**	**204.43**
ADR - Vehicle (Assembly, Disposal, and Recycling)	16.2	17.7	17.4	17.4	17.3	17.2	9.14	9.47	9.16	9.02	8.87	8.76
ADR	16.2	17.7	17.4	17.4	17.3	17.2	9.14	9.47	9.16	9.02	8.87	8.76
Total	**453.4**	**378.6**	**342.4**	**313.6**	**313.5**	**314.3**	**312.40**	**259.47**	**233.65**	**213.20**	**212.90**	**213.20**

For an LCV with a gasoline engine, the GREET® model calculates CO_2 emissions of 312 g/km for 2019. Just under 19% of these emissions are attributable to the well-to-pump section. The operation of the ICE LCV accounts for around 78% of the total CO_2 emissions. For the period 2019 to 2050, the GREET® model calculates a reduction in CO_2 emissions of 32% to 213 g/km. Total energy consumption falls by approximately 33% to 62 MJ/hkm in this period.

GREET® model 2021: total energy use & CO_2 emissions output data – MCV Diesel

MCV - Diesel	Total Energy (MJ/hkm)						CO_2 (g/km)					
	2019	2030	2035	2040	2045	2050	2019	2030	2035	2040	2045	2050
WTP	**159.9**	**132.2**	**125.2**	**125.1**	**124.9**	**113.7**	**106.85**	**88.07**	**83.19**	**82.94**	**82.69**	**74.80**
Mode - Regular	867.7	744.1	709.6	709.6	709.6	629.3	649.05	556.47	530.62	530.62	530.62	470.48
Operation Only	867.7	744.1	709.6	709.6	709.6	629.3	649.05	556.47	530.62	530.62	530.62	470.48
WTW	**1,027.6**	**876.3**	**834.8**	**834.6**	**834.5**	**743.0**	**755.90**	**644.54**	**613.81**	**613.56**	**613.31**	**545.28**
Components - Vehicle Body	7.6	7.5	7.4	7.4	7.4	7.4	4.08	3.91	3.87	3.85	3.83	3.81
Components - Powertrain System	3.4	3.4	3.4	3.4	3.4	3.4	1.68	1.63	1.62	1.61	1.61	1.60
Components - Transmission System/Gearbox	0.8	0.8	0.8	0.8	0.8	0.8	0.54	0.52	0.51	0.51	0.51	0.50
Components - Chassis (w/o battery)	13.5	13.3	13.3	13.2	13.2	13.2	9.62	9.27	9.18	9.14	9.10	9.08
Components - Traction Motor (HEV, PHEV, EV, FCV)	0.2	0.2	0.2	0.2	0.2	0.2	0.15	0.14	0.14	0.14	0.14	0.14
Components - Electronic Controller (HEV, PHEV, EV, FCV)	0.0	0.0	0.0	0.0	0.0	0.0	0.01	0.01	0.01	0.01	0.01	0.01
Components - Van/Box	16.2	16.2	16.2	16.2	16.2	16.2	8.79	8.77	8.74	8.72	8.71	8.70
Components - Lift-gates	2.1	2.1	2.0	2.0	2.0	2.0	1.70	1.63	1.61	1.60	1.59	1.59
Components	43.9	43.6	43.4	43.3	43.3	43.3	26.56	25.89	25.68	25.59	25.49	25.43
ADR - Vehicle (Assembly, Disposal, and Recycling)	53.4	50.6	49.7	49.4	49.1	48.8	31.39	26.66	25.50	24.97	24.43	24.02
ADR	53.4	50.6	49.7	49.4	49.1	48.8	31.39	26.66	25.50	24.97	24.43	24.02
Fluids - Engine Oil	1.0	1.0	1.0	1.0	1.0	1.0	0.59	0.59	0.59	0.59	0.59	0.59
Fluids - Steer Axle Lubricant	0.6	0.6	0.6	0.6	0.6	0.6	0.33	0.32	0.32	0.32	0.32	0.32
Fluids - Drive Axle Lubricant	0.0	0.0	0.0	0.0	0.0	0.0	0.02	0.02	0.02	0.02	0.02	0.02
Fluids - Inter-axle/Drive-shaft Lubricant	1.1	1.1	1.1	1.1	1.1	1.1	0.65	0.65	0.65	0.64	0.64	0.65
Fluids - Wheel-end Lubricant: Steer Axle	0.1	0.1	0.1	0.1	0.1	0.1	-	-	-	-	-	-
Fluids - Wheel-end Lubricant: Drive Axle	0.1	0.1	0.1	0.1	0.1	0.1	0.03	0.03	0.03	0.03	0.03	0.03
Fluids - Transmission Fluid	0.1	0.1	0.1	0.1	0.1	0.1	0.04	0.04	0.04	0.04	0.04	0.04
Fluids - Engine/Powertrain Coolant	0.1	0.1	0.1	0.1	0.1	0.1	0.03	0.03	0.03	0.03	0.03	0.03
Fluids - Coolant Cleaner	0.3	0.3	0.3	0.3	0.3	0.3	0.19	0.19	0.19	0.19	0.19	0.19
Fluids - Windshield Fluid	0.7	0.7	0.7	0.7	0.7	0.7	0.09	0.08	0.08	0.08	0.08	0.08
Fluids	4.1	4.1	4.1	4.1	4.1	4.1	2.01	1.99	1.98	1.98	1.98	1.98
Battery - Lead-Acid (Vehicle Battery Assembly)	0.9	0.9	0.9	0.9	0.9	0.9	0.38	0.35	0.35	0.34	0.34	0.34
Battery - Lithium-ion Battery Bill-of-material	0.9	0.9	0.9	0.9	0.9	0.9	0.53	0.51	0.50	0.49	0.49	0.49
Battery - Lithium Ion (Vehicle Battery Assembling Part)	0.1	0.1	0.1	0.1	0.1	0.1	0.08	0.07	0.07	0.07	0.07	0.07
Battery	1.9	1.9	1.9	1.9	1.9	1.9	0.98	0.93	0.91	0.91	0.90	0.90
Total	**1,130.8**	**976.4**	**933.8**	**933.3**	**932.8**	**841.0**	**816.84**	**700.00**	**667.88**	**667.00**	**666.11**	**597.61**

For a diesel MCV, the GREET® model calculates CO_2 emissions of 817 g/km for 2019. Around 13% of these emissions are attributable to the well-to-pump section. Around 80% of the total CO_2 emissions are caused by the operation of the ICE MCV. In the case of CO_2 emissions attributable to the vehicle process chain, the item "ADR - Vehicle (Assembly, Disposal, and Recycling)" dominates with just over 50% in this section. For the period 2019 to 2050, the GREET® model calculates a decrease in total CO_2 emissions of 27% to 598 g/km. Total energy consumption falls by approximately 29% to 114 MJ/hkm in this period.

GREET® model 2021: total energy use & CO_2 emissions output data – HCV Diesel

HCV - Diesel	Total Energy (MJ/hkm)						CO_2 (g/km)					
	2019	2030	2035	2040	2045	2050	2019	2030	2035	2040	2045	2050
WTP	**251.7**	**167.4**	**151.0**	**150.9**	**150.7**	**139.1**	**168.19**	**111.55**	**100.36**	**100.06**	**99.76**	**91.50**
Mode - Regular	1,365.8	942.4	856.0	856.0	856.0	769.8	1,020.13	703.57	638.84	638.84	638.84	574.22
Operation Only	1,365.8	942.4	856.0	856.0	856.0	769.8	1,020.13	703.57	638.84	638.84	638.84	574.22
WTW	**1,617.5**	**1,109.8**	**1,007.0**	**1,006.9**	**1,006.7**	**908.9**	**1,188.32**	**815.11**	**739.20**	**738.90**	**738.59**	**665.72**
Components - Powertrain System	3.6	3.6	3.6	3.6	3.6	3.6	1.90	1.84	1.83	1.82	1.81	1.80
Components - Transmission System/Gearbox	0.8	0.8	0.8	0.8	0.8	0.8	0.59	0.57	0.56	0.56	0.55	0.55
Components - Chassis (w/o battery)	15.0	14.8	14.7	14.7	14.7	14.7	10.67	10.31	10.22	10.18	10.14	10.11
Components - Vehicle Body	5.2	5.2	5.2	5.2	5.1	5.1	2.75	2.64	2.61	2.60	2.59	2.58
Components	24.7	24.4	24.3	24.3	24.2	24.2	15.92	15.36	15.22	15.15	15.09	15.05
ADR - Vehicle (Assembly, Disposal, and Recycling)	61.3	58.1	57.1	56.7	56.4	56.0	36.10	30.61	29.26	28.63	28.01	27.53
ADR	61.3	58.1	57.1	56.7	56.4	56.0	36.10	30.61	29.26	28.63	28.01	27.53
Fluids - Engine Oil	2.8	2.8	2.8	2.8	2.8	2.8	1.62	1.61	1.61	1.61	1.60	1.61
Fluids - Steer Axle Lubricant	0.9	0.9	0.9	0.9	0.9	0.9	0.54	0.54	0.54	0.54	0.54	0.54
Fluids - Drive Axle Lubricant	0.1	0.1	0.1	0.1	0.1	0.1	0.08	0.08	0.08	0.08	0.08	0.08
Fluids - Inter-axle/Drive-shaft Lubricant	0.4	0.4	0.4	0.4	0.4	0.4	0.22	0.22	0.22	0.22	0.22	0.22
Fluids - Wheel-end Lubricant: Steer Axle	0.1	0.1	0.1	0.1	0.1	0.1	0.03	0.03	0.03	0.03	0.03	0.03
Fluids - Wheel-end Lubricant: Drive Axle	0.1	0.1	0.1	0.1	0.1	0.1	0.07	0.07	0.07	0.07	0.07	0.07
Fluids - Transmission Fluid	0.0	0.0	0.0	0.0	0.0	0.0	0.03	0.03	0.02	0.02	0.02	0.03
Fluids - Engine/Powertrain Coolant	0.2	0.2	0.2	0.2	0.2	0.2	0.04	0.04	0.04	0.04	0.04	0.04
Fluids - Coolant Cleaner	0.2	0.2	0.2	0.2	0.2	0.2	0.10	0.10	0.10	0.10	0.10	0.10
Fluids - Windshield Fluid	0.1	0.1	0.1	0.1	0.1	0.1	0.01	0.01	0.01	0.01	0.01	0.01
Fluids - Adhesives	0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00	0.00	0.00
Fluids	4.9	4.8	4.8	4.8	4.8	4.9	2.73	2.71	2.70	2.70	2.70	2.71
Battery - Lead-Acid (Vehicle Battery Assembly)	0.2	0.2	0.2	0.2	0.2	0.2	0.11	0.10	0.10	0.10	0.10	0.10
Battery	0.2	0.2	0.2	0.2	0.2	0.2	0.11	0.10	0.10	0.10	0.10	0.10
Others - Trailer Body	10.8	10.9	10.9	10.9	10.9	10.9	5.87	5.87	5.85	5.84	5.83	5.82
Others - Trailer Chassis	16.9	16.7	16.7	16.6	16.6	16.6	11.57	11.25	11.16	11.13	11.09	11.07
Others - Trailer Auxiliary	0.8	0.8	0.8	0.8	0.8	0.8	0.53	0.51	0.50	0.50	0.50	0.49
Others - Drive Axle Lubricant	0.1	0.1	0.1	0.1	0.1	0.1	0.08	0.08	0.08	0.08	0.08	0.08
Others - Wheel-end Lubricant: Drive Axle	0.1	0.1	0.1	0.1	0.1	0.1	0.07	0.07	0.07	0.07	0.07	0.07
Others - Vehicle (Assembly, Disposal, and Recycling)	1.4	1.4	1.3	1.3	1.3	1.3	0.84	0.72	0.69	0.68	0.67	0.65
Others	30.3	30.0	29.9	29.9	29.9	29.9	18.96	18.48	18.35	18.28	18.22	18.18
Total	**1,738.9**	**1,227.5**	**1,123.4**	**1,122.9**	**1,122.2**	**1,024.1**	**1,262.13**	**882.37**	**804.82**	**803.77**	**802.71**	**729.29**

For a diesel HCV, the GREET® model calculates CO_2 emissions of 1,262 g/km for 2019. Just over 13% of these emissions are attributable to the well-to-pump section. The operation of the ICE HCV accounts for almost 82% of the total CO_2 emissions. The item "ADR - Vehicle (Assembly, Disposal, and Recycling)" dominates the CO_2 emissions attributable to the vehicle process chain with 49% in this section. For the period 2019 to 2050, the GREET® model calculates a decrease in total CO_2

emissions of 42% to 729 g/km. Total energy consumption falls by approximately 45% to 139 MJ/hkm in this period.

GREET® model 2021: total energy use & CO_2 emissions output data – School bus Diesel

School bus - Diesel	Total Energy (MJ/hkm)						CO_2 (g/km)					
	2019	2030	2035	2040	2045	2050	2019	2030	2035	2040	2045	2050
WTP	**203.2**	**191.2**	**180.9**	**180.7**	**180.5**	**171.2**	**135.77**	**127.41**	**120.18**	**119.82**	**119.46**	**112.62**
Mode - Regular	1,102.5	1,076.4	1,025.0	1,025.0	1,025.0	947.5	824.51	805.05	766.55	119.82	766.55	708.41
Operation Only	1,102.5	1,076.4	1,025.0	1,025.0	1,025.0	947.5	824.51	805.05	766.55	766.55	766.55	708.41
WTW	**1,305.7**	**1,267.6**	**1,205.9**	**1,205.7**	**1,205.5**	**1,118.7**	**960.28**	**932.47**	**886.73**	**886.37**	**886.01**	**821.03**
ADR - Vehicle (Assembly, Disposal, and Recycling)	86.8	82.3	80.8	80.3	79.8	79.4	51.04	43.36	41.47	40.60	39.73	39.06
ADR	86.8	82.3	80.8	80.3	79.8	79.4	51.04	43.36	41.47	40.60	39.73	39.06
Total	**1,392.4**	**1,349.9**	**1,286.7**	**1,286.1**	**1,285.3**	**1,198.0**	**1,011.32**	**975.82**	**928.20**	**926.97**	**925.73**	**860.09**

For a diesel-powered school bus, the GREET® model calculates CO_2 emissions of 1,011 g/km for 2019. A good 13% of these emissions are attributable to the well-to-pump section. The operation of the ICE HCV accounts for almost 82% of the total CO_2 emissions. The item "ADR - Vehicle (Assembly, Disposal, and Recycling)" accounts for 5% of the total CO_2 emissions. For the period 2019 to 2050, the GREET® model calculates a decrease in total CO_2 emissions of 15% to 860 g/km. Total energy consumption falls by approximately 16% to 171 MJ/hkm in this period.

GREET® model 2021: total energy use & CO_2 emissions output data – Transit bus Diesel

Transit bus - Diesel	Total Energy (MJ/hkm)						CO_2 (g/km)					
	2019	2030	2035	2040	2045	2050	2019	2030	2035	2040	2045	2050
WTP	**245.3**	**212.0**	**202.7**	**202.4**	**202.2**	**188.0**	**164.92**	**141.28**	**134.67**	**134.26**	**133.86**	**123.64**
Mode - Regular	1,342.5	1,193.6	1,148.6	1,148.6	1,148.6	1,040.2	1,001.66	890.11	856.40	856.40	856.40	775.15
Operation Only	1,342.5	1,193.6	1,148.6	1,148.6	1,148.6	1,040.2	1,001.66	890.11	856.40	856.40	856.40	775.15
WTW	**1,587.8**	**1,405.6**	**1,351.3**	**1,351.0**	**1,350.8**	**1,228.2**	**1,166.58**	**1,031.40**	**991.06**	**990.66**	**990.25**	**898.79**
ADR - Vehicle (Assembly, Disposal, and Recycling)	119.4	112.2	110.2	109.6	108.9	108.2	67.65	59.12	56.55	55.36	54.17	53.26
ADR	119.4	112.2	110.2	109.6	108.9	108.2	67.65	59.12	56.55	55.36	54.17	53.26
Total	**1,707.1**	**1,517.8**	**1,461.5**	**1,460.6**	**1,459.7**	**1,336.4**	**1,234.24**	**1,090.52**	**1,047.61**	**1,046.02**	**1,044.43**	**952.05**

For a diesel transit bus, the GREET® model calculates CO_2 emissions of 1,234 g/km for 2019. A good 13% of these emissions are attributable to the well-to-pump sector. The operation of the ICE HCV accounts for around 81% of the total CO_2 emissions. The item "ADR - Vehicle (Assembly, Disposal, and Recycling)" accounts for just over 5%. For the period 2019 to 2050, the GREET® model calculates a decrease in total CO_2 emissions by 23% to 952g/km. Total energy consumption also falls by approximately 23% to 188 MJ/hkm in this period.