A comparative analysis of alternative powertrains and fuels of public busses from economic, environmental and energetic point of view

A Master Thesis submitted for the degree of
Master of Science

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Vienna, 2021

Affidavit

I, Aleksandra Krnić, hereby declare:

That I am the sole author of the present Thesis: "*A comparative analysis of alternative powertrains and fuels for public busses from economic, environmental and energetic point of view*", 83 pages, using sources and tools which are referenced in this Thesis.

I have not prior to this date submitted this Master Thesis as an examination paper in any form in Austria or abroad.

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Abstract

Global warming and very poor air quality cause many diseases and catastrophes on the planet. As such they are the most important drivers of thorough research and evaluation of the influence of bus transportation on the environment.

The core objective of this thesis was to make a comparison and evaluation of energy carriers (gas, hydrogen and electricity) from renewable energy sources (i.e. wind, solar, water) with conventional fuels (oil) used in different kinds of buses. The comparison and evaluation were done based on economic and environmental analysis.

The key question arose from the general concerns: Could it make any sense and reason to proceed and execute the alternative bus technology development and research despite the high-purchase bus costs? Does sustainable bus transport truly offer an environmental advantage with respect to air pollution? Does secondary environmental impact (such as noise level) play a role as well?

This work provides an economic and an environmental assessment of different alternative bus technologies in comparison to conventional diesel buses. The analyses included a technological overview, economic assessment and environmental evaluation. The analyses were focused on greenhouse gas (GHG) emissions and air pollution. This thesis investigated the most significant advantages and disadvantages of alternative- versus conventional bus technologies. As the transport sector is one of the major generators of GHG emissions and air pollution, the switch to battery-electric buses or fuel-cells electric buses could lead to the reduction of local air pollution and global GHG emissions.

The total cost of ownership analysis indicates that natural gas buses are already competitive with conventional buses. The battery-electric buses will become competitive starting from 2030. Battery-electric and fuel-cell-electric bus are arguably capable of satisfying the current operational requirements in the city public bus sector. However, the major barrier is the initial cost of buses. A battery-electric bus is considered the most appropriate alternative type of bus from economic and environmental points of view. The currently high total cost of ownership of fuel-cells-electric bus is the major challenge to achieving a lower total cost of ownership to more competitive level. Major impact parameters are documented and used for the economic and environmental assessment of alternative bus technologies. Moreover, the scenarios of the development of the future costs of ownership and emission reductions are derived. Further technological research of alternative fuels and sustainable bus technologies are turning points in the future of the public transportation sector, hence they are a part of this research topic.

The significant potential of GHG reduction emission in the future is probably to be found in road transportation. Comprehensive decarbonisation of buses is technically possible in the long term through the increased utilization of electricity and hydrogen from renewable sources of energy. This development is needed in order to achieve the EU government's energy and climate targets up to the year 2050. Battery-electric technology will advance such that the total cost of ownership will decline and the driving range will improve. Implementing an electric bus is completely different from buying a conventional bus. Good cooperation between energy suppliers, regulatory bodies and public bus sector is crucial in terms of environmental goals.

Kurzfassung

Globale Erwärmung und sehr schlechte Luftqualität verursachen viele Krankheiten und Katastrophen auf unserem Planeten. Als solche sind sie die wichtigsten Treiber für eine gründliche Erforschung und Bewertung des Einflusses des Busverkehrs auf die Umwelt. Das Kernziel dieser Arbeit war es, einen Vergleich und eine Bewertung von Energieträgern (Gas, Wasserstoff und Elektrizität) aus erneuerbaren Energiequellen (d.h. Wind, Sonne, Wasser) mit konventionellen Kraftstoffen (Öl), die in verschiedenen Arten von Bussen verwendet werden, durchzuführen. Der Vergleich und die Bewertung erfolgten auf Basis einer ökonomischen und ökologischen Analyse.

Die Schlüsselfrage ergab sich aus den allgemeinen Bedenken: Ist es sinnvoll und vernünftig, die Entwicklung und Erforschung alternativer Bustechnologien trotz der hohen Anschaffungskosten für Busse fortzusetzen und durchzuführen? Bietet der nachhaltige Busverkehr tatsächlich einen Umweltvorteil in Bezug auf die Luftverschmutzung? Spielen auch sekundäre Umweltauswirkungen (wie z.B. der Lärmpegel) eine Rolle?

Diese Arbeit liefert eine ökonomische und eine ökologische Bewertung verschiedener alternativer Bus-Technologien im Vergleich zu konventionellen Dieselbussen. Die Analysen umfassten einen technologischen Überblick, eine wirtschaftliche Bewertung und eine Umweltbewertung. Der Schwerpunkt der Analysen lag auf den Treibhausgasemissionen (THG) und der Luftverschmutzung. Diese Arbeit untersuchte die wichtigsten Vor- und Nachteile von alternativen gegenüber konventionellen Bustechnologien. Da der Verkehrssektor einer der Hauptverursacher von THG-Emissionen und Luftverschmutzung ist, könnte der Umstieg auf batterieelektrische Busse oder Elektrobusse mit Brennstoffzellen zu einer Reduzierung der lokalen Luftverschmutzung und der globalen THG-Emissionen führen.

Die Analyse der Gesamtbetriebskosten zeigt, dass Erdgasbusse bereits jetzt wettbewerbsfähig mit konventionellen Bussen sind. Die batterieelektrischen Busse werden ab 2030 wettbewerbsfähig werden. Batterieelektrische und brennstoffzellenelektrische Busse sind zweifellos in der Lage, die aktuellen Betriebsanforderungen im öffentlichen Stadtbussektor zu erfüllen. Das größte Hindernis sind jedoch die Anschaffungskosten der Busse. Ein batterieelektrischer Bus wird unter wirtschaftlichen und ökologischen Gesichtspunkten als der geeignetste alternative Bustyp angesehen. Die derzeit hohen Gesamtbetriebskosten von Brennstoffzellen-Elektrobussen sind die größte Herausforderung, um die Gesamtbetriebskosten auf ein wettbewerbsfähigeres Niveau zu senken. Die wichtigsten Einflussparameter werden dokumentiert und für die ökonomische und ökologische Bewertung der alternativen Bustechnologien verwendet. Darüber hinaus werden Szenarien der Entwicklung der zukünftigen Betriebskosten und Emissionsreduzierungen abgeleitet. Die weitere technologische Erforschung alternativer Kraftstoffe und nachhaltiger Bustechnologien sind Wendepunkte in der Zukunft des ÖPNV-Sektors, daher sind sie ein Teil dieses Forschungsthemas.

Das signifikante Potenzial zur Reduktion von THG-Emissionen in der Zukunft liegt wahrscheinlich im Straßenverkehr. Eine umfassende Dekarbonisierung von Bussen ist durch die verstärkte Nutzung von Strom und Wasserstoff aus erneuerbaren Energiequellen langfristig technisch möglich. Diese Entwicklung ist notwendig, um die Energie- und Klimaziele der EU-Regierung bis zum Jahr 2050 zu erreichen. Die batterieelektrische Technologie wird sich so weiterentwickeln, dass die Gesamtbetriebskosten sinken und die Reichweite steigt. Die Einführung eines Elektrobusses ist etwas völlig anderes als die Anschaffung eines konventionellen Busses. Eine gute Zusammenarbeit zwischen Energieversorgern, Regulierungsbehörden und dem öffentlichen Bussektor ist im Hinblick auf die Umweltziele entscheidend.

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Abbreviations

ATR	Auto Thermal Reforming
BEB	Battery electric Bus
CEP	Clean Energy Partnership
CO_2	Carbon-dioxid
CSC	Coal Steam Cycle
DB	Diesel Bus
DF	Diesel Fuel
EFTA	European Free Trade Association
FCEB	Fuel cell electrics Bus
GHG	Greenhouses Gases
GREET	Greenhouse gases, Regulated Emissions and Energy use in Transportation
GSR	Gasoline Steam Reforming
IEA	International Energy Agency
LCC	Life Cycle Cost
NGB	Natural Gas Bus
NGCC	Natural Gas Combined Cycle
NGSR	Natural Gas Steam Reforming
NMVOC	Non-methane volatile organic compounds
NO_X	Nitrogen Oxides
O&M	Operational and Maintenance
OEM	Original Equipment Manufacturer
PM	Particle Matter
PMI	Preventive Maintenance Inspection
RED	Renewable Energy Directive
SMR	Steam Methane Reforming
TCO	Total Cost of Ownership
TTW	Tank to Wheel
WTT	Well to Tank
WTW	Well To Wheel
ZEV	Zero Emission Vehicles

1 Introduction

1.1 Motivation

There are many reasons for the transition from conventional buses to alternative buses; such as climate changes, global warming, unstable oil price, geopolitical issues, increasing air pollution etc[1]. The possible solution to solve these problems lies in fuels from renewable energy resources. Alternative fuels have been suggested for bus transportation and many studies have been made to evaluate them.

The choice as to which type of bus technology will be used is an important issue for public transit agencies in terms of budget impact, operating performance, bus purchasing decisions, related refuelling and depot infrastructure. The very important outcome is the level of greenhouse gas and air pollutant emissions. Alternative fuels might play a role in the future of the transportation sector, such as electricity and hydrogen; since they both seem to suggest improvement of energy efficiency and lower imprint on environmental issues. The road transportation sector is facing challenges of satisfying the ever-increasing transportation demands on the one hand and achieving greenhouse gas (GHG) emission and air pollution reduction targets without compromising economic and technological development on the other hand.

The escalation of energy-related GHG emissions is one of the concerns which arise from the increasing transportation demand. One of the possible solutions to significantly reduce GHG is the use of energy carriers from renewable sources for the transportation sector. Achieving EU reduction targets for GHG emissions and air pollution, along with acceptable noise levels generated by operating busses, represents a complex challenge.

Costs are marked as critical because of the very high purchase price of vehicle with alternative energy carrier in comparison with the purchase price of conventional diesel bus. Charging station infrastructure should be available everywhere for uninterrupted transportation. In order to opt for the best solution for bus transportation, infrastructure costs will be included in the analysis. The higher purchase price must be justified with a lower level of emission and lower consumption of energy. The specifics of how this could be achieved will be discussed further in this paper.

The main motivations of using alternative buses instead of internal combustion buses (diesel buses) are climate changes, the increasing restriction on air pollutants emission, security of supply and environmental concerns. There are a few challenges; such as infrastructure of electric buses charging station and their availability, and high purchase costs of alternative powertrain, that will provide lower corrective maintenance cost based on a comprehensive automated diagnosis of the bus, however, automated diagnostic is not a part of the analysis. With gradually disposing of diesel buses, environmentally negative issues will be eliminated, such as:

- high GHG emissions,
- high air pollution,
- additional problems are unstable fossil fuel price and energy import dependency.

Figure 1 presents the main drivers of alternative powertrains. The motivation for further development of battery-electric or fuel-cell-electric buses could be from economic, environmental and energetic reasons.

Operation and maintenance costs (replacement costs of battery and fuel-cell) are very high for electric buses and one of the goals is to decrease these costs as well as purchase costs. Optimization in fuel consumption could be enforced on all types, especially on conventional buses. After fuel optimization, total cost of ownership (TCO) should be lower for electric buses. Automated diagnostic of vehicles should decrease maintenance costs because of easier recognition of the issue and reduced repair maintenance time.

One of the main concerns is limited quantity of fossil fuels resources worldwide and a limited amount of fossil fuel countries of origin. To avoid all possible challenges of fossil fuel supply, the solution is found in alternative fuels obtained from renewable energy resources.

Global warming and air pollution are the significant environmental drivers of greener transportation. CO_2 emission and other air pollutants such as NMVOCs, SO_X, NH_3, CO, NO_X and PM, could be decreased by switching from conventional buses to electric buses. The level of noise produced by electric vehicles is significantly lower than by diesel or natural gas buses.

Economy:
Low investment/O&M costs
Lower fuel consumption
TCO optimization for vehicle costs
Extensive automated diagnosis

Energy (Resource conservation):
Limited fossil fuel
Increasing consumption worldwide
Unstable fossil fuel price
Fuel imports depend on politically unstable countries

Environments:
Local emission
Global emission
Noise

Figure 1: Main drivers for further development for transition on alternatively fueled buses (Source: Putz (2018))[2]

1.2 Core objective of work

The core objective of this work was to document all advantages and disadvantages of alternative buses regarding economic and environmental issues and to analyze future developments using scenarios. This thesis will observe four types of technology: internal combustion engine buses running on diesel, natural gas buses run on natural gas, fuel-cell-electric buses running on hydrogen and battery-electric buses using electricity. In addition, this thesis will explain that the investment in “green” technology will have more advantages and positive results than the utilization of conventional buses. Economic and environmental analysis in this thesis will show the current situation in bus transportation. In order to investigate the benefits of replacing diesel buses with alternative buses, several reports and scientific papers have been researched. All important parameters of economic and environmental assessments have been considered in this thesis. The calculations used in this study are implicitly related to the manufacturing process of the vehicles and raw material resources emission (oil, gas, hydrogen and electricity).

Proposed scenarios show all benefits that incorporate alternative vehicles in the future of bus transportation.

The following questions will be investigated:

- General bus market:
  What is the current state of the art of bus technology in Europe? What is the share of conventional buses versus alternative buses?

- Economic aspects:
  What are the significant cost parameters related to bus utilization? What are the expected energy cost of energy and bus technologies in the future?

- Environmental issues:
  What are the most significant energy carriers regarding environmental protection? What is the best type of bus for environmental protection measured by GHG emissions and air pollutants?

- Bus technology:
  What are the advantages/disadvantages of the different bus technologies?

- Legal regulatory body:
  What are the proper policies for the promotion of alternative solutions? What is the regulatory perspective regarding new types of technologies? What are the required circumstances in order to achieve the EU targets for emission reduction?

The most important literature used in this study is:

- European Environmental Agency (GHG emission in EU and data about the current situation in EU)
- Official Journal of the European Union (Legislative, Regulations and Directions in EU)
- Ralph Pütz, „Ökologischer und ökonomischer Vergleich der SWG-Busflotte in Abhängigkeit ihrer Zusammensetzung auf den Zeithorizonten „heute“ und „mittelfristig“, 2018 (The basic inputs parameters for calculation)
- Arjan van Velzen, Jan Anne Annema, Geerten van de Kaa, Bert van Wee, “Proposing a more comprehensive future total cost of ownership estimation framework for electric vehicles”, 2019 (Method of total costs of ownership)
- Rolf Diemer, Florian Dittrich, “Transport in the European Union Current Trends and Issues”, 2019 (The most significant data about state of the art in EU)

1.3 Structure of the work

This work is organized as follows:

First chapter: The introduction describes the main reasons and motivation of researching this topic, the core objective and the main questions of the work, as well as the structure of the work itself.

The second chapter presents the state of the art information in the European transport sector and provides technical descriptions of all alternative types of buses.

Third chapter: The methodological approach of economic and environmental analysis with calculations is thoroughly described in this chapter.

Fourth chapter: The economic aspects are considered in the calculation of vehicles costs, energy cost, production costs and maintenance costs. The meaning of each cost is explained in detail. Starting from the current costs, the future costs are estimated showing which buses could be feasible in the future from an economic point of view.

Fifth chapter: The environmental and energy analysis regarding GHG emission is explained as regards all the negative influences on the quality of life. A comparison of four types of buses is used to determine the most environmentally friendly technology regarding GHG emission.

Sixth chapter: The initial data of air pollutants (for example, NO_X and PM analyses) is used to establish the possible scenario in the future regarding air pollution reduction.

Seventh chapter: Legal issues, some of the most important policies and regulations are presented.

Eight chapter: Based on the analyses conducted, major conclusions are derived.

2 Public buses in EU: State of the art

The demand for transportation increased drastically in the last century in the European Union as well as worldwide.

Road transportation is an important sector for the economy of the EU. Transportation services imply a complex network of around 1.2 million private and public companies in the EU, employing around 11 million people and providing goods and services to citizens and businesses and its trading partner[3]. In the EU the average age of a working bus is 11.4 years[4]. With one bus capable of replacing 30 cars on the road, buses help ease traffic congestion[4]. EU Commission suggested a strategic long-term vision for a climate-neutral economy by 2050. Road infrastructure through the EU has been degrading due to lack of maintenance[3]. It has led to the deterioration of the roads in many EU countries, which causes a higher risk of accidence, congestions and noise. A big challenge is to adjust infrastructure for new mobility patterns and alternative vehicles.

The main goals for the EU bus public transportation sector are to reduce GHG emission and local air pollution, decreasing the number of accidents and reducing noise pollution. Buses are the most used form of public transportation in the EU, both in urban and rural areas. Bus transportation is a cost effective and flexible form of public transportation with minimal efforts to launch new lines or routes. 8% of passenger transportation on land in the EU is performed by buses. 55.7% of all public transportation journey in the EU is made by buses. In 2017 there were around 892 900 buses in circulation on the EU roads[5].

2.1 New bus registrations

In 2019, 85% of all new medium and heavy buses registered in the EU were running on diesel, while the market share of petrol in this segment was close to zero. All alternatively powered buses combined accounted for 15% of the EU bus market. Of all buses currently in use in the EU 4.8% is hybrid buses, 4% is electric buses, 6.2% is another alternative fuels (compressed natural gas, LPG, biofuels and ethanol vehicles)[4].

Figure 2 illustrates the share of the new buses, registered in 2019 in the EU.

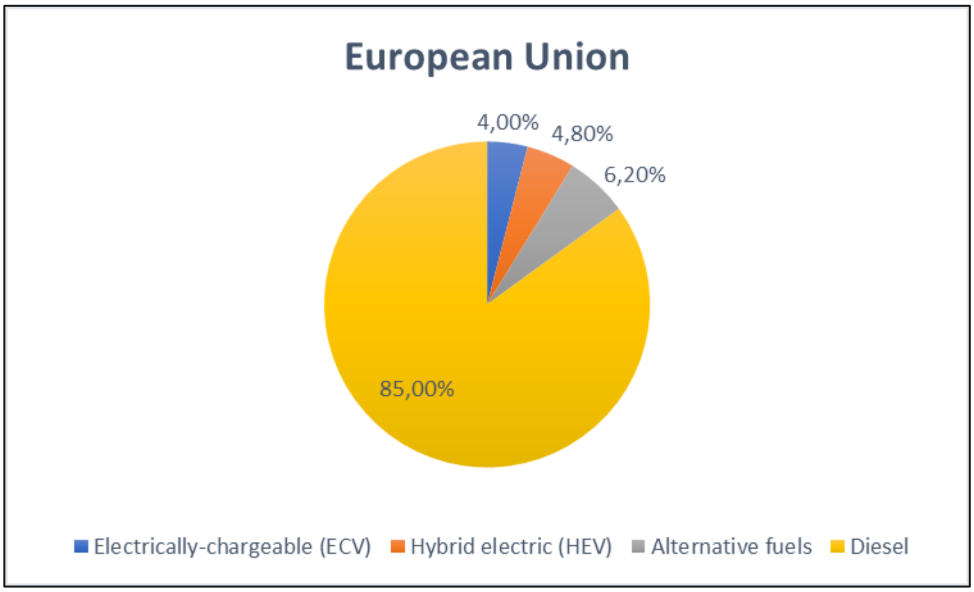

Figure 2: New bus registration in the EU by fuel type in 2019 (Source: European Automobile Manufactures Association, 2020)[4]

In 2019 in the EU, the number of diesel buses decreased by 3.1% than in 2018. Four countries had big losses in the diesel segment, for example: Spain (-13.8%), the United Kingdom (-12%), Italy (-11.8%) and Germany (-10.1%). France had a growth (+2.4%) in registrations of new diesel buses. Across the entire EU, only eight petrol buses were sold in 2019[4]. In the year 2019, registration of electrical buses in the EU increased by 170.5% (594 buses sold in 2018, 1607 buses sold in 2019). The Netherlands was the biggest market for these vehicles with 381 electric buses registered in 2019, then comes France with 285 buses and in Germany where 187 buses were registered. These three EU countries accounted for more than half of all the electrically chargeable busses sold last year in the whole EU[4].

In the year 2019, 1918 hybrid buses were sold in the EU, an increase of 59.7% more than in the year 2018. The total hybrid electric buses have a share of 4.8% of the total buses in usage in the EU. Hybrid electric buses are registered in only six EU countries: Spain (427 hybrid electric buses), Belgium (371 hybrid electric buses), Italy (255 hybrid electric buses), France (210 hybrid electric buses), Germany (125 hybrid electric buses) and Netherlands (125 hybrid electric buses). In other EU countries no hybrid electric bus was registered in the year 2019[4].

Of all new buses sold in the EU in 2019 6.2% were alternative fuels (CNG, LNG, biofuels and ethanol). This is an increase of 67.9% (2504 buses) of alternative buses sold in the year 2019, compared to the previous year. All of these alternative buses are powered by natural gas. The largest EU markets for natural gas buses are France (585 natural gas buses), Spain (463 natural gas buses), Italy (303 natural gas buses) and Sweden (284 natural gas buses). The increased percentage usage of natural gas buses was 283.8%[4].

In Figure 3, the types of registered new alternative buses within the EU (except Bulgaria, Croatia, Malta, Lithuania and Iceland) are presented. The vertical axis shows the number of buses and the horizontal axis shows the type of buses (electric buses-ECB, hybrid electric buses-HEB and alternative bus-AB). Data for Bulgaria, Croatia, Malta, Lithuania and Iceland are not available, 2019 data for the EU still include the United Kingdom.

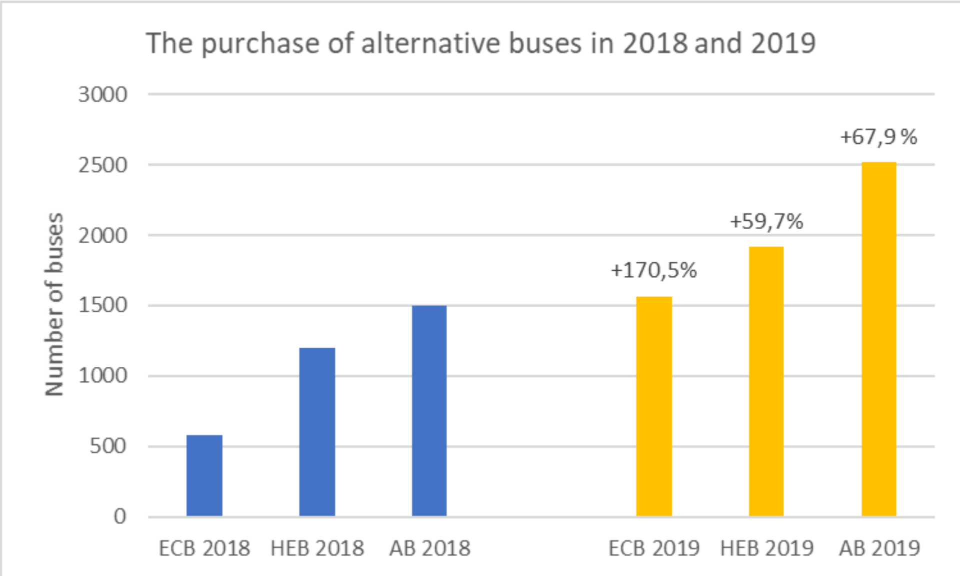

Figure 3: The purchase of alternative buses in 2019 and 2018 (Source: European Automobile Manufacturers Association (2020)) [4]

Table 1 presents newly registered buses in each EU country (except: Bulgaria, Croatia, Malta, Lithuania and Iceland) for two years, 2018 and 2019. Slovenia and Luxemburg did not register new buses so the existing buses were operational.

This table includes all EU and EFTA memberships (data for the intergovernmental organisation of Iceland, Liechtenstein, Norway and Switzerland).

Table 1: New fuel-type bus registrations in 2018 and 2019: EU and EFTA (European Free Trade Association)[4]

	Electrically-chargable			Hybrid electric			Alternative fuels			Petrol			Diesel		
	2019	2018	% change	2019	2018	% change	2019	2018	% change	2019	2018	% change	2019	2018	% change
Austria	60	18	233,33	0	0	n/a	18	0	n/a	0	0	n/a	1085	1107	-2,00
Belgium	37	14	164,29	371	221	67,90	2	6	-66,70	0	0	n/a	900	819	9,90
Cyprus	0	n/a	n/a	0	n/a	n/a	0	n/a	n/a	1	n/a	n/a	18	n/a	n/a
Czech Republic	4	n/a	0	0	n/a	n/a	273	n/a	n/a	0	n/a	n/a	835	n/a	n/a
Denmark	100	2	4900	0	0	n/a	0	0	n/a	0	0	n/a	442	575	-23,10
Estonia	0	0	0	0	0	n/a	76	0	n/a	0	0	n/a	104	99	5,10
Finland	40	1	3900	0	0	n/a	17	5	240,00	0	0	n/a	536	469	14,30
France	285	95	200	210	266	-21,10	585	301	94,40	0	0	n/a	5702	5568	2,40
Germany	187	43	334,88	454	227	100,00	62	46	34,80	7	4	75,00	5717	6360	-10,10
Greece	0	1	0	0	0	n/a	0	0	n/a	0	0	n/a	363	262	38,50
Hungary	0	1	-100	0	0	n/a	0	0	n/a	0	0	n/a	705	666	5,90
Ireland	0	0	0	0	0	n/a	0	0	n/a	0	0	n/a	445	446	-0,20
Italy	65	53	22,64	255	19	1.242,10	303	383	-20,90	0	0	n/a	3626	4112	-11,80
Latvia	2	4	-50	0	0	n/a	7	0	n/a	0	0	n/a	87	110	-20,9
Luxembourg	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Netherlands	381	103	269,90	125	0	n/a	10	45	-77,80	0	0	n/a	419	414	1,20
Poland	54	63	-14,29	51	200	-74,50	185	55	236,40	0	0	n/a	2114	2366	-10,65
Portugal	17	10	70	10	0	n/a	206	129	59,70	0	0	n/a	368	371	-0,80
Romania	50	11	354,5	0	0	n/a	1	0	n/a	0	0	n/a	710	364	95,10
Slovakia	0	18	-100	0	0	n/a	12	14	-14,30	0	0	n/a	293	319	-8,20
Slovenia	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Spain	103	30	243,33	427	260	64,20	463	407	13,80	0	0	n/a	2268	2632	-13,80
Sweden	98	36	172,22	15	8	87,50	284	74	283,80	0	0	n/a	921	813	13,30
United kingdom	124	91	36,26	n/a	0	n/a	n/a	0	n/a	0	0	n/a	6465	7349	-12,00
European Union	1607	594	170,538721	1918	1201	59,70	2504	1491	67,90	8	4	100,00	34123	35221	-3,10
Norway	157	12	1.208,3	0	0	n/a	187	25	648,00	1	0	n/a	1954	965	102,50
Switzerland	10	18	-44,40	103	38	171,10	1	3	-66,70	1	1	0,00	532	621	-14,30
EFTA	167	30	456,70	103	38	171,10	188	28	571,4	2	1	100,00	2486	1586	56,70
EU+EFTA	1774	624	184,30	2021	1239	63,10	2692	1519	77,20	10	5	100,00	36609	36807	-0,50

Clearly, Denmark and Finland had significant differences in the percentage of electric buses registered. However, the Netherlands France and Germany had the largest number of new electric buses registered. While there was increase in the number of registered hybrid electric buses in Belgium, Germany, Italy and Spain.

Table 2 presents the type of buses sold in the observed countries in the EU in the year 2019. Some countries decided to opt for diesel engine only, like Greece, Hungary, Ireland. However, countries like the Netherlands, Estonia and Belgium prefer alternative fuel sources. In the year 2019, of all the registered busses, diesel-powered buses accounted for 85%.

Table 2: Market share of new registered buses in EU in 2019[4]

	ELECTRICALLY CHARGEABLE	HYBRID ELECTRIC	ALTERNATIVE FUELS	PETROL	DIESEL
Austria	5.2%	0.0%	1.5%	0.0%	93.3%
Belgium	2.8%	28.3%	0.2%	0.0%	68.7%
Cyprus	0.0%	0.0%	0.0%	5.3%	94.7%
Czech Republic	0.4%	0.0%	24.6%	0.0%	75.1%
Denmark	18.5%	0.0%	0.0%	0.0%	81.5%
Estonia	0.0%	0.0%	42.2%	0.0%	57.8%
Finland	6.7%	0.0%	2.9%	0.0%	90.4%
France	4.2%	3.1%	8.6%	0.0%	84.1%
Germany	2.9%	7.1%	1.0%	0.1%	89.0%
Greece	0.0%	0.0%	0.0%	0.0%	100.0%
Hungary	0.0%	0.0%	0.0%	0.0%	100.0%
Ireland	0.0%	0.0%	0.0%	0.0%	100.0%
Italy	1.5%	6.0%	7.1%	0.0%	85.3%
Latvia	2.1%	0.0%	7.3%	0.0%	90.6%
Luxembourg	–	–	–	–	–
Netherlands	40.7%	13.4%	1.1%	0.0%	44.8%
Poland	2.2%	2.1%	7.7%	0.0%	87.9%
Portugal	2.8%	1.7%	34.3%	0.0%	61.2%
Romania	6.6%	0.0%	0.1%	0.0%	93.3%
Slovakia	0.0%	0.0%	3.9%	0.0%	96.1%
Slovenia	–	–	–	–	–
Spain	3.2%	13.1%	14.2%	0.0%	69.5%
Sweden	7.4%	1.1%	21.5%	0.0%	69.9%
United Kingdom	1.9%	0.0%	0.0%	0.0%	98.1%
EUROPEAN UNION	4.0%	4.8%	6.2%	0.0%	85.0%
Norway	6.8%	0.0%	8.1%	0.0%	85.0%
Switzerland	1.5%	15.9%	0.2%	0.2%	82.2%
EFTA	5.7%	3.5%	6.4%	0.1%	84.4%
EU+EFTA	4.1%	4.7%	6.2%	0.0%	84.9%

Road traffic is currently the greatest source of traffic noise in the EU, both in rural and urban areas. A high level of noise could harm human health. Almost 90 million people living in cities were exposed to long-term average road traffic noise that accounts for more than 55 dB. During the night, over 83 million people were exposed to road noise levels exceeding 50 dB[69].

Figure 4 illustrates the bus share in the road transportation sector in each country. It could be concluded that more developed countries have lower usage of buses than the EU 28 Commission referent value 9.3% (orange line on the graphic). The year 2016 marks the low level of alternative buses in operation.

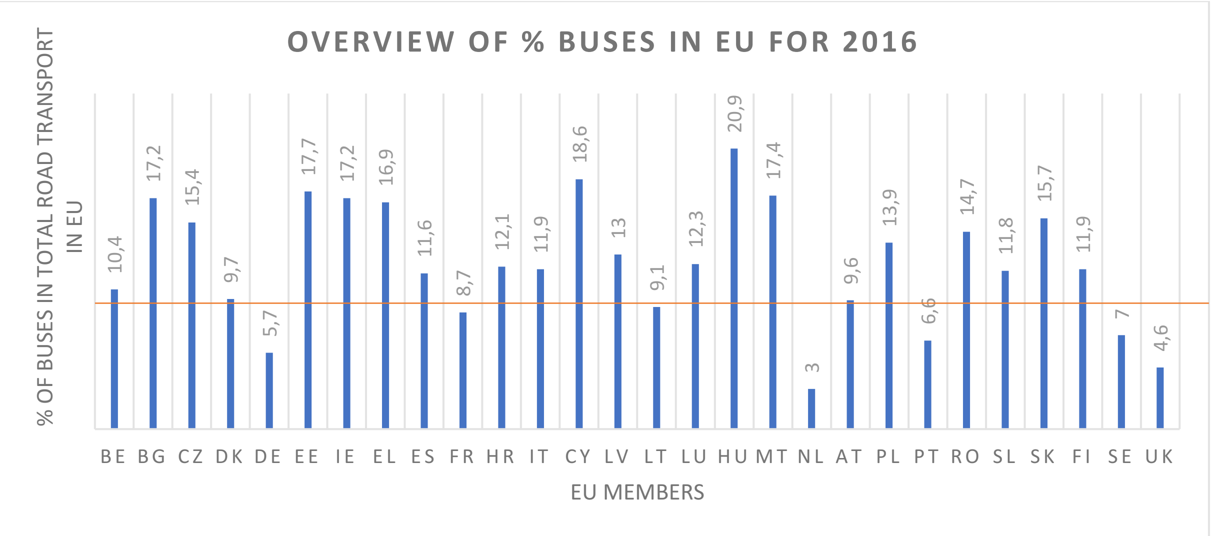

Figure 4: Overview of the percentage of buses in total road transport in the EU (Source: Diemer and Dittrich (2016))[3]

The high density of the traffic network creates challenges for the infrastructure, especially in cities and municipalities. The focus is on long-distance between bus stations, which in many places do not meet the requirements for modernity and capacity. In order to market continuous development dynamically, further investments in infrastructure are necessary. For the municipalities, the focus should be on the opportunities that long-distance buses bring along.

The EU Commission has made legislative suggestions as a guide to access the road market. Revision of road charging rules and better social legislation for road transportation is one of them. The EU will force this transition through targeted legislation and supporting measures, including infrastructure investment, research and innovation. This will ensure that the most “green”, connected and automated mobility solutions, transportation equipment and vehicles be developed and manufactured in Europe. There are few legislative initiatives specifically targeting road transportation (Communication: Europe on the move - An agenda for a socially fair transition towards clean, competitive and connected mobility for all; Smarter Road Infrastructure Charging – Revision of Euro vignette Directive (1999/62); Promoting the European electronic toll service (EETS) — Recast of the Directive on the interoperability of electronic road toll systems in the Community (2004/52)). Initiative measures that can improve the bus transportation sector will be considered:

- Market opening
- Better application and implementation of existing rules
- Setting road charging system and technologies

- Improvement of road safety
- Environmental sustainability

The EU Commission proposes new standards of CO_2 emission for cars, bus and trucks after 2020, which will aid members of the EU to achieve their goals regarding reducing emissions. In May 2017, the European Commission proposed a regulation on the reduction of CO_2 emissions from new heavy-duty vehicles. The European Parliament strongly supports suggested measures for reducing the environmental impact of heavy-duty vehicles. The Clean Mobility Packages presented in November 2017 contain a proposal for post-2020 CO_2 limits and revision of the Directive 2009/33/EC on the promotion of clean and energy efficient road transportation vehicles, which addresses public procurement of energy-efficient buses and trucks.

The revision of clean vehicle directives[3] documents includes measures for the increase of public demands for alternative vehicles in the EU countries. These measures include a plan for investment in alternative fuel infrastructure and a plan for installation of a fast and interoperable network of charging station across the EU.

Fuel-cell and hydrogen joint undertaking (FCH) has derived a project (FCH 2 JU) to implement an optimal research and innovation program to bring FCH technologies to the point of market readiness by 2020. The core objectives of the FCH 2 JU project were to reduce the production cost of the fuel-cell system, increasing their lifetime and fuel-cell efficiency to levels which can compete with conventional technologies. There are many benefits of using fuel-cell electric buses, like: zero tailpipe emission (CO_2 emissions savings and only water emitted), no need for new street infrastructure, rapid fuelling, 300 km and more without refueling and comfort for passengers due to reduced level of noise. In this project, 26 buses were deployed in 5 European cities (London, Oslo, Milan, Aargau, Hamburg). Later, (JIVE 2) 152 buses were added across 14 European cities[62]. The highlights of the project are:

- the reliability of fuel-cell electric buses (alternative buses considered as a direct replacement of diesel buses)
- reduced fuel cell bus capital costs
- fuel consumption falls to appoximately 6.5kgH_2/100 km (from 8-9 kgH_2/100 km seen in CHIC project)
- fuel cell and battery life is 7 years[62].

In the EU, in the year 2020, 300-400 fuel-cell-electric buses were in operation[63]. Since its first deployment in the 1990s, purchasing prices for fuel-cell-electric buses have fallen by more than 75%. TCO is expected to come down to 3.3 Euro per kilometre in 2030[63].

In 2017, the EU could count only 2 100 electric buses which represents 1.6% of bus fleet. Electric bus adoption in urban road transportation is growing in the EU. In 2018, the European electric bus market increased by 48% compared to 2017 and the year 2019 saw a tripling in the number of electric bus registration in Western Europe[64]. In 2020, based on the first three quarters, over 2 000 battery-electric buses were registered in the western countries of the EU, which means that around 4 000 electric buses were running the road[64]. Overall in 2020, 72.9% of all new medium and heavy buses registered in EU ran on diesel, down almost 10 % points from 2019. Battery-electric buses made up 6.1% of total new bus registration and hybrid buses have share from 9.5%. All alternatively powered buses present 11.4%, nearly of them powered by natural gas[15].

2.2 Technical description of alternative buses

This chapter explains the main technical characteristic of alternative buses, natural gas buses (NGB), FCEB (fuel-cell-electric buses) and BEB (battery-electric buses). With the following brief explanations, it will be easier to compare and understand these three different bus technologies, their principles of operations as well as technical specifications. This chapter provides some important differences between alternative and conventional diesel buses.

2.2.1 Natural gas buses

An alternative fuel bus that uses compressed natural gas (CNG) or liquefied natural gas (LNG) is a natural gas bus (NGB). In natural gas-powered buses, energy is released by combustion of essentially methane gas CH_4 fuel with oxygen O_2 from the air to produce carbon dioxide CO_2 and water vapor H_2O in an internal combustion engine. Existing gasoline engine vehicles could be converted to CNG or LNG engine vehicles. They can be dedicated to natural gas or biofuel only, running on either gasoline or natural gas. This conversion will require minimal changes in bus configuration.

Natural gas vehicles emit 20-29% less CO_2 than diesel and gasoline vehicles[6]. Their emissions are cleaner, with lower emissions of carbon and lower particulate matter pollution per equivalent distance traveled. In addition; there is generally less wasted fuel. CNG is the cleanest burning transportation fuel. Due to lower carbon content, CNG produces lesser emissions than petroleum. CNG produces 95% fewer tailpipe emissions than diesel fuel. However, the cost (monetary, environmental, pre-existing infrastructure) of distribution, compression, and cooling must be considered.

Natural gas buses are like diesel vehicles in terms of power, acceleration and driving speed. They both can transport passengers on routes of long distance as opposed to battery-electric buses, which have a limited reachable distance. With all these benefits of CNG buses, it is expectable that more cities will replace their diesel buses at the end of their lifecycle with natural gas buses[65].Natural gas buses are approximately 10 dB quieter than a comparable conventional diesel bus. This noise reduction helps to improve the quality of life for drivers, passengers and neighborhoods.

The compact design of natural gas buses creates more space for the CNG storage system. In some models of buses, the few large gas cylinders stored in the roof can carry up to 1.875 l in fuel. That provides a minimum range of 500 km[66]. Because of lower fuel costs than diesel fuel costs, savings in TCO of around 15% can be expected over a period of 10 years and distance of 60 000 km annually.

2.2.2 Fuel-cell-electric buses

A fuel-cell-electric bus (FCEB) is an electric bus that includes both a hydrogen fuel cell and batteries/capacitors. In such hybrid architecture, the fuel cell is responsible for the energy of the vehicle operation, while the batteries/capacitors are responsible for the motors to meet rapid acceleration and gradients. By using a fuel cell with a battery, the size of each can be optimized depending on the purpose and required driven distance.

Available types of FCEB on the market:

- buses with a small battery and a large fuel cell (for instance 150 kW);
- buses with a supercapacitor (in additional to the battery) and a fuel cell (for instance 75kW);
- buses with a large battery and a fuel cell (as range extender).

There are no local emissions because the fuel leaves only water and heat as byproduct. The electric energy keeps the batteries charged. The by-product heat is stored on the brake resistors and is used to maintain heating in the inside of the bus. The batteries also provide storage for regenerated braking energy. All the energy required for the bus to operate is provided by hydrogen stored on board (Figure 5). Hydrogen offers higher energy density compared to electrical storage systems such as batteries. This ensures a longer distance travelled in comparison with BEB, where the battery is used for energy storage. Refueling of the bus takes around 7 minutes for typical refill, with technical development being optimized to 5 minute or even less. A centralized hydrogen refueling station may not be good enough in the future to overcome the main obstacles with a bad infrastructure for a vehicle driven by hydrogen. An FCEB belongs to ZEV because the fuel cell generates only water as an emission.

Hydrogen can be produced from a range of ultra-low carbon routes. This includes renewable electricity, biomass and other hydrocarbons including carbon capture and storage; however, currently most of the produced hydrogen is from fossil sources of energy. When fueled by hydrogen produced via any of these alternatives' routes, an FCEB provides a green hydrogen solution to public transportation.

An FCEB is a good choice according to zero emission solution that offers an operation close to that of a diesel bus and hence is marketed as the closest option for zero emission to replace diesel engines.

Figure 5 shows a fuel-cell-electric bus with the most common configuration. Fuel-cell vehicles use hydrogen gas to power an electric motor. Unlike conventional vehicles which run on gasoline or diesel, fuel-cell buses combine hydrogen and oxygen to produce electricity, which runs a motor. The green arrow shows the flow of hydrogen gas from the tank to the exhaust pipe.

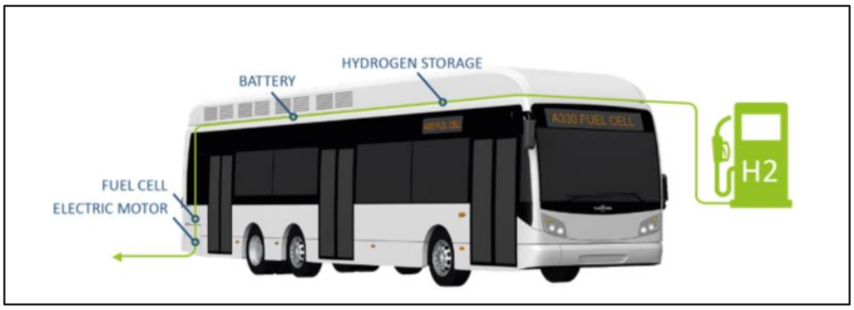

Figure 5: How an hydrogen fuel-cell bus works (Source: https://www.fuelcellbuses.eu (2020)) [7]

The hydrogen tanks are usually stored on the roof of the bus, while the fuel-cell and electric engine are located at the back of the bus. Benefits of using an FCEB could be classified into environmental, operational flexibility, passengers' comfort and compliance with geopolitical challenges.

Environmental benefits: Air quality improvements (no toxic tailpipe emissions/only water vapor); GHG emission reductions (with the potential to fully decarbonize public transportation when hydrogen is generated from alternative energy sources); Noise reduction (fuel-cell-electric buses are quiet in comparison to diesel buses - DB).

Benefit of operational flexibility: Fuel-cell-electric buses have the longest range (> 300 km) / no need to return to the depot during daily service; shortest refueling times (< 10 min); a performance comparable to conventional buses (speed and acceleration); flexibility of service: no need for on-street infrastructure; a regenerative braking system that allows for a better efficiency of the vehicle. Passenger comfort includes lower level of noise and lack of vibration. An FCEB reduces perceived noise levels by almost two thirds compared to a conventional diesel bus.

Compliance with geopolitical challenges: National and local regulations on low-carbon mobility and better air quality with low level of pollution and a long-term strategy focused on reducing vulnerability to fossil fuel imports. Additional obstacles for using FCEBs are high purchase cost and fuel-cell replacement cost. In the EU, an FCEB is in operation in Germany, France, Switzerland, UK, Netherlands, Norway and Italy. All other countries have “planned” strategies for using and refueling already installed charging station.

Different concepts for refueling infrastructure exist that are suitable for different levels of hydrogen requirements. Hydrogen can be generated on-site or produced centrally and delivered on-site. Hydrogen could be delivered as liquid (by tanker truck) or compressed gas (by cylinders).
Thus, an FCEB can be operated more like a conventional DB. An FCEB offers the best operational performance compared to other zero emission options. In terms of acceleration, speed and gradeability, an FCEB performs like a conventional DB. Due to very low noise and vibration levels, an FCEB offers a smooth driving experience and a high degree of passenger comfort[63]. In short, there are few benefits of investing in an FCEB and transition to FCEBs from conventional buses. The first one is political. There are requirements for reducing emissions in EU generated by road transportation. The second one is environment. FCEBs provide green cities, cleaner public transportation and reduced noise. The third one is economic, which reduces external costs of public transportation.

2.2.3 Battery-electric buses

Long term goals are total independence from oil and zero tailpipe emissions technologies required by 2050. Battery-Electric Buses (BEBs) satisfy these two goals. The method is simple: an electric motor powered by a battery replaces the Internal Combustion Engine Bus (ICEB) with a tank, and the vehicle is plugged to a charging spot when it is not in use. They have many advantages: they are highly efficient, do not produce tailpipe emissions which is beneficial for local and global air quality, have good accelerating performance, and drive with low level of noise. Additionally, they can be charged overnight on low cost electricity produced by any type of power station, preferably from renewable energy resources. However, despite these advantages, BEBs also face significant challenges. Electricity storage is still expensive, and the charging of the battery is time consuming. The driving distance of these vehicles is limited due to lower amount of energy use per km compared with conventional diesel buses (for a longer battery lifetime higher capacity is needed, this means heavier weight which is more expensive). A charging spot infrastructure must be in place before any market penetration, and the corresponding investment in infrastructure is important.

The energy storage system of a BEB and technological readiness of batteries are crucial problem in the development and market penetration of BEBs. The key characteristics of electric batteries are the energy density, the power density, the cycle life, calendar life, and the cost per kWh. All these parameters evaluated concludes the performance of a BEB. Electric motors have many advantages in comparison with DB engines. The conversion efficiency from electrical to mechanical energy is high (70% to 95%)[8]. They have high torque and power density and better torque characteristics at low speed. It is possible to use electric motors as generators during breaking in order to recover energy. A BEB produces lower level of noise and offers a rapid and smooth acceleration. Furthermore, electric motors are robust and reliable with reasonable cost.

Power electronics are the intermediate between the battery, a DC current source, and the AC motor. A DC/AC inverter controls the voltage fed to the engine through switching devices. Control algorithms specific to each type of motor ensure that it operates at the highest efficiency. The efficiency of power electronics is typically between 95% and 98%.

Reducing battery weight is crucial for electric vehicles in order to maximize their range within a given battery and to improve aerodynamical efficiency of the bus. The size and the weight of the battery will be reduced by the substitution of its materials, i.e. steel to be replaced by aluminum, plastic and composites.

Techno-economic influence of an increased number of BEBs on the grid is one of concern. The power required during charging or during fast charging is significant. Local transformers are the weakest link in the transmission and distribution system: such an increase in power demand could cause their overheating and destruction. A possible imbalance of the 3-phase system with the new loads should be equally distributed. To solve these issues, a detailed calculation of the local system distribution should be carried out. End-users should be encouraged to charge their vehicles overnight through dedicated system of price. Charging must start at different hours of the night in the same neighborhood to avoid overload on the grid. System Operators of the electricity network should be informed about penetration of BEB in different areas in order to plan the capacity of the network.

3 Methodology

In this study, a comparative analysis of economic and environmental performances, on four types of urban passenger buses was carried out: conventional diesel, natural gas, fuel-cell-electric and battery-electric buses. The scope of the life-cycle assessment and costs analysis includes both the manufacturing and the operations of the buses. Operating characteristics such as capacity, fuel consumption, maintenance requirements are included. Manufacturing characteristics; such as, size, technical components, batteries, powertrain, and exhaust systems, are also included. The parameters corresponding to these characteristics were adapted from the existing studies and are based on assumptions as regards the available data.

The methodology, thoroughly explained in the following chapter, will create a complete picture of all relevant emissions (CO_2, NO_X and PM). The averaged emission generated for an entire bus life cycle is the scope of this study. Besides environmental issues, the overall costs will also be discussed. This includes bus transportation existing costs as well as predicted costs for the future.

This thesis presents an humble scientific contribution regarding better understanding of the current situation in emission contribution of bus transportation and the rationale of costs included in the whole bus life cycle, from manufacturing up to disposal.

3.1 Economic assessment

This thesis will show calculations for the total costs of ownership of the four bus types referenced earlier. Economic evaluation and comparison will be done by calculating the TCO for different type of buses through present and future scenarios.

Putz (2018)[2] discussed the economic and environmental comparison of all four types of buses mentioned above. In his study, he provided all relevant parameters for TCO calculation and made analysis in the year 2018 as well as in the future years until 2030 and beyond. Mahmoud et al. (2016)[9] provided an analysis of six alternative technologies: diesel, hybrid (parallel and series), compressed natural gas (CNG), battery-electric, and hydrogen fuel-cell. Their work was focused on a comparative analysis of emission, energy, and operation. However, it excluded cost estimation. Lifecycle emission and cost assessments of electric buses, among other alternatives, is now taking considerable academic attention. For example, Lajunen and Timothy (2016)[10] concluded that hybrid and battery-electric buses are favored with respect to their lifecycle cost, operation, and environmental measures for bus transit application. Even when considering different charging methods, battery-electric technology is still favored by Lajunen (2018)[11]. Sjoerd and Rob (2017)[12] confirmed that lithium-ion batteries price decreased by 79%. According to their study, after the year 2010, BEBs were placed as the most viable option and this made electrical buses to be more convenient for bus agencies. According to Nurhadi et al. (2014)[13], the lower operation costs of BEB for the highest yearly average driven distance buses compensate for higher manufacturing costs while this is still not the case with FCEB. In order to evaluate the cost offset, TCO calculation has a key role on the transportation electrification process. Anden et al. (2019)[14] revealed that FCEB and BEB battery and fuel-cell price still have a great impact on TCO. Battery lifetime is shorter than power electronics lifetime and they must be replaced with the aim to extend the bus optimum operation. These replacements are previously planned for the TCO determination and they must be met. Battery lifetime must be managed with an aim to minimize the operation costs and to meet the battery aging constraints to optimize and further decrease TCO. Lajunen (2017)[15] in his research presents a lifecycle costs analysis for a fleet operation of electric city buses in different operating routes. There are defined charging power and battery requirements as well as energy consumption and lifecycle costs. Bus travel agency mostly consider the substantial initial cost of BEB above many other costs involved in bus TCO. TCO methodology is often used to analyze the competitiveness of BEBs. A TCO aims to describe the full costs of ownership and to inform the consumer on which vehicle costs less. TCO methodology is a suitable method for comparing different vehicle technologies. When constructing a TCO analysis, different costs at different points in time are assumed. Future costs need to be calculated using a discounted formula approximating the value of money in time, the present value formula. The study ”How Total is a Total Cost of Ownership?” presents TCO for alternative vehicle technologies as well as its extension with external costs according to the vehicle ownership and utilization. TCO in the future depends on real discount rate and is expressed separately for onetime costs and recurring costs (Clerc et al. (2016)[16]). This approach is not used in this study. There are two distinct types of TCO methods, consumer-oriented TCO method and society-oriented TCO method. Consumer-oriented TCO method is focused on the difference in cost the consumer should pay depending on the various vehicle technologies at his disposal. Society-oriented TCO method is based on the relationship between cost of different vehicles technologies and their social impact. In this thesis focus is laid on the consumer oriented TCO methodology.

The cost analysis conducted in the scope of this work encompass current as well as future total cost of bus ownership. The costs are critical component and one of the major impact parameters of the purchase of buses. In this economic assessment, the following cost calculation assumptions are involved: energy costs (market fuel price and CO_2 tax emission costs), maintenance costs (constant value assumed), purchase costs (based on market analysis and customer requirements). Based on known current costs, a TCO calculation could be applied for total costs analysis with discount factor which presents costs variation in the future.

Accumulated TCO analysis additive cost of a bus throughout its lifetime. The simplest model is depictured in Figure 6, all relevant parameters for TCO calculations in this study were considered. Replacement costs include a cost of new battery and fuel cell.

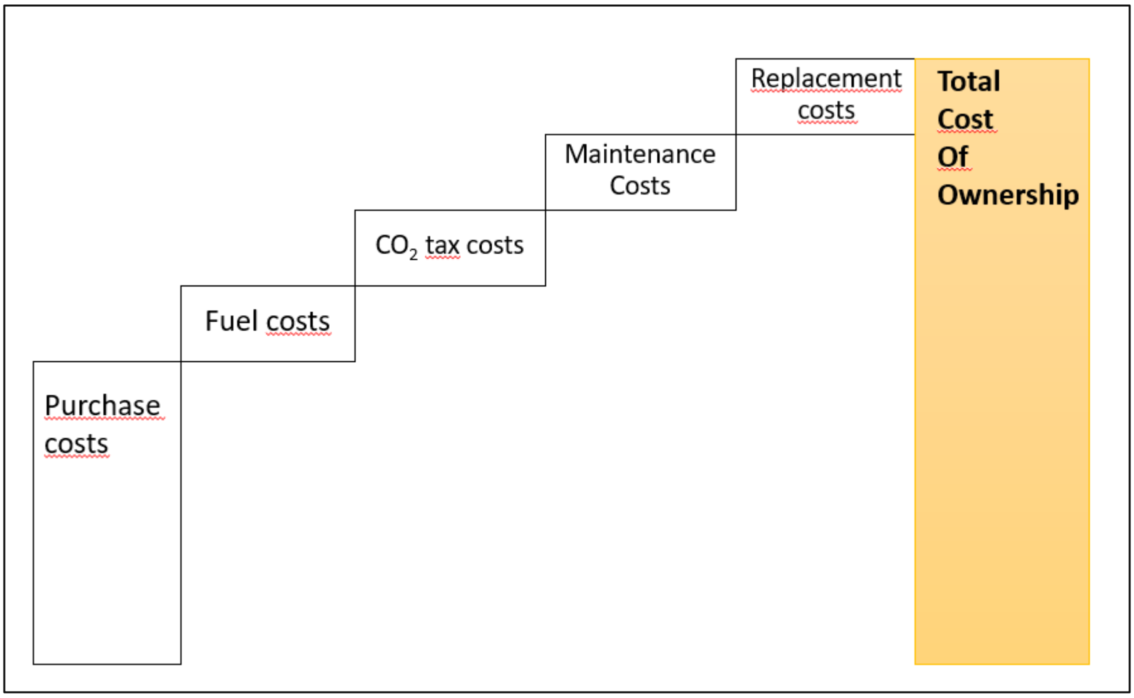

Figure 6: Total costs of ownership used in this thesis

All lifetime costs of the bus are included in the TCO analysis. Bus purchase costs are expenses specifically designated on a company's financial statement as an extraordinary or one-time expense the company does not expect to continue over time, at least not on a regular basis. Fuel costs and operating and maintenance costs are normal, ongoing expenses required for bus operation. These expenses typically appear on a company's income statement as indirect costs and are also factored into the balance sheet and cash flow statements.

Disposal costs will not be in the scope of this thesis and will be neglected. After n-th years, bus should be dismantled, and disposal costs will not be included. It could be justified as negligible in comparison to very high manufacturing costs (purchase price) as well as fuel costs, CO_2 tax costs and preventative and corrective maintenance. In the chapter *Economical aspect,* the input parameter used for TCO are described in detail.

The explained figure could be mathematically presented as[10]:

$$TCO = C_{purchase} + \sum_{y=0}^{n} C_{op\_y} * (1 + d_{rate})^{-y} \quad (1)$$

$$C_{op\_y} = \left(Range_y * \left(C_{fuel\_y} + C_{CO2\_y} + C_{maint\_y} + C_{rep\_y}\right)\right) \quad (2)$$

With following parameters in equation:

TCO ... *Total costs of ownership (€)*
$C_{purchase}$ ... *Bus purchase cost (€)*
C_{op_y}... *Operating costs (€)*
C_{rep_y} ... *Technology replacement costs (€)*
d_{rate} ... *Discount factor*
y ... *Year from first year up to nth year of usage*
$Range_y$ ... *Yearly driven distance (km)*
C_{fuel_y} ... *Fuel costs per driven distance (€/km)*
C_{maint_y} ... *Maintenance costs per driven distance (€/km)*
C_{CO2_y} ... *Annually CO_2 emission costs for bus(€/km)*

Fuel costs per km are calculated with equation (3):

$$C_{fuel\_y} = FC \; * PF_y \tag{3}$$

where

FC ..... *Fuel consumption per km* $\left(\frac{l}{km}\right)$
PF_y ...... *Fuel price* $\left(\frac{€}{l}\right)$

This equation is used for every type of fuel, just instead l, natural gas is expressed in m^3, hydrogen in kg, electricity in kWh respectively.

CO_2 costs are expressed with the following equations:

$$C_{CO2\_y} = C\_SP_{CO2_y} * CO_{2\_em} \tag{4}$$

With

$C\_SP_{CO2\_y}$..... *Specific CO_2 costs in* y^{th} *year* $\left(\frac{€}{ton}\right)$
CO_{2_em} ..... *Total CO_2 bus emission* $\left(\frac{kg}{km}\right)$

This equation calculates the costs compared between all four types of vehicles. Some assumptions have been kept in these equations:

- Daily range for city bus is usually 165 km which means 60 000 km per year
- Life duration of city buses in EU on average is 14 years
- Average speed is 16.7 km/h
- It is in common sense 14 year *($n = 14$)* as optimal lifetime for one bus in operation
- Cost for disposal can be neglected in relation to the purchase and the maintenance costs.

Using these assumptions, economic and environmental issues will be calculated [2]

One of the main additional costs for alternative buses is battery and fuel cell. The first scenario might be TCO calculated with battery replacement and second scenario TCO without battery replacement for BEB and FCEB. Costs for additional battery and fuel cell, here called C_{rep_y}, is not repetitive costs and should be in the seventh year of bus utilization (for $y = 7, C_{rep\_7} \neq 0$; for $y \neq 7, C_{rep_y} = 0$). With these scenarios one should confirm the differences in TCO, if there are any.

Discount factor is used to calculate a present value of future costs. It is not a fixed number, rather it depends on the bus technology and the type of the bus [17].

3.2 Environmental assessment

Economic, environmental and energy factors are particularly significant when a new powertrain and new fuel solutions are analyzed. In comparative analysis between the different types of buses, attention is usually on total costs of ownership and on impact on environment.

Torchio and Santarelli (2010)[1] provided an environmental assessment of bus life cycle technology considering the vehicle life cycle (material flow) and the fuel life cycle (energy flow). Vehicle life cycle includes material production, vehicle assembly, maintenance, distribution and vehicle disposal. The fuel life cycle, which is known as well-to-wheels (WTW) analysis ("well" from energy producing to the "wheel" energy delivering to the end user) will be presented in two segments:

- well-to-tank (WTT - energy consumption and emissions to extract raw substance, to transport them, to produce the desired fuel, to deliver the fuel to customers, etc.)
- tank-to-wheel (TTW - energy consumptions and emission during usage of a vehicle)[1].

In the bus sector the focus is often on fuel life cycle, because this part is most influential in comparison with vehicle life cycle. But both will be included in the calculation of costs comparison, in GHG emission and air pollution comparison. WTW emission index calculates the total pollutant emitted from a fuel production pathway and utilization.

$$WTW = WTT + TTW$$

where:

WTW .... *Well-To-Wheels* $(\frac{g}{km})$

WTT .... *Well-To-Tank* $(\frac{g}{km})$

TTW .... *Tank-To-Wheel* $(\frac{g}{km})$

For example, energy consumption due to the fuel life cycle usage represents 80% to 93% of total energy consumption by investigation from Melo et al. (2014)[17]. Mahmoud et al. (2016)[9] studied alternative powertrains and provided a detailed review of various performance features for three categories of electric buses: hybrid, fuel-cell and battery. Also included are performance feature of those buses. The results obtained from the calculation show that an hybrid electric bus provides an average of 20.8% reduction in GHG emission and 2.1% savings in energy consumption. With renewable based hydrogen, fuel-cell-electric bus contributes to a 75% reduction in GHG emissions and 27.7% savings in energy consumption, which is slightly better than with the NGSR (natural gas steam reforming which is used as energy source fossil hydrocarbons to produce hydrogen) based hydrogen, which contributes to 73.8% and 15.4% reduction in emission and fuel consumptions, respectively. The study of methods for calculating the emissions of transportation in the Netherlands from Klein et al. (2018)[30] described all emission factors per vehicle class. The authors claim that the years of usage has a significant influence on the extra emissions. This is caused by "cold start" and by "hot driving" depending on the year of use, emission per vehicle kilometer travelled for a hot engine and average number of cold starts per kilometer travelled. This thesis will assume mostly hot driving which means no often shut downs and startups of the bus.

A case study in North Rhine-Westphalia Germany calculated the most important exhausted emission input parameters. Those are mileage of vehicle and emission factor. This study from Breuer et al. (2020)[53] was focused on NO_X and PM air pollutants.

Figure 7 explains the steps of WTT (from row material to fuel for vehicle) and TTW (burning fuel and driving) process. All these steps generate some amount of emission. Total GHG emitted or air pollution generated is calculated by the summation of WTT and TTW emissions. The European commission's science and knowledge service describes well-to-wheel analysis as shown in Figure 7. WTW analysis focuses on TTW, as the major contributor to lifetime energy use and GHG emissions. There is no estimate of "cost of society" such as health, social or other speculative cost areas [12].

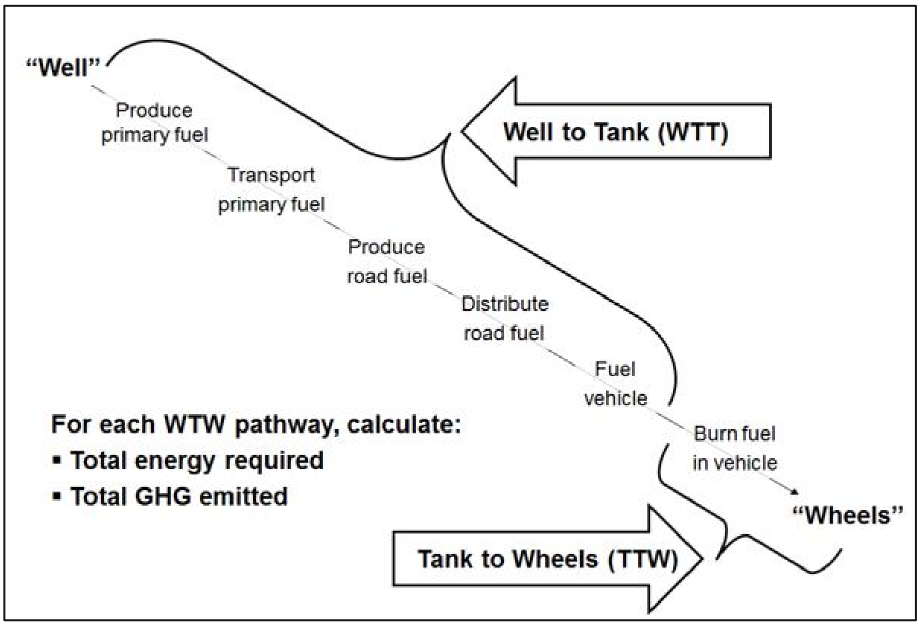

*Figure 7: WTW Analysis-graphic representation (Source: Sjoerd and Rob(*2017)) [12]

However, the large number of urban transit buses are currently equipped with high displacement engines and are in operation from morning until night, which contributes lots of greenhouse gases and emits air pollutants[31]. The environmental performance of different technologies has received considerable attention in recent years from both academics and services providers. The main motivation for the transition, that this paper has to asses and analyze, is the environmental benefits of electric powertrains. In this section, energy supply for each bus is assessed based on both WTT and TTW aspects using different scenarios for energy supply.

In order to calculate the total GHG emission and air pollution the next operations will be analyzed and applied in this thesis[2]:

- Bus manufacturing
- Well-To-Tank (WTT)
- Tank-to-Wheel (TTW)

Figure 8 provides an overview of LCA in bus technology applied in this study.

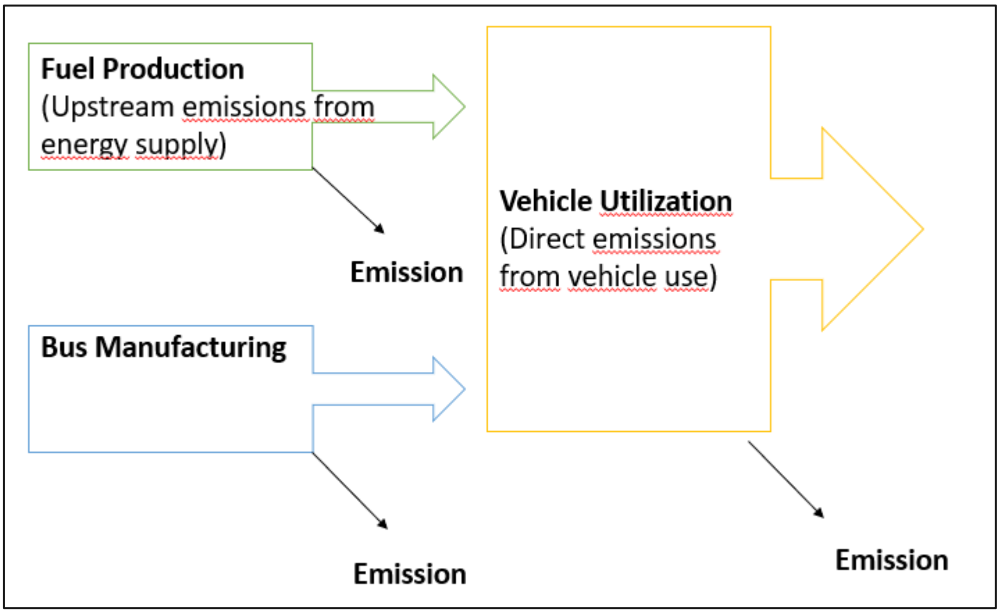

Figure 8: Flow diagram: Cradle to grave LCA overview

The scope of this work does not include emissions produced during bus disposal and bus maintenance. These are not a part of the study due to very low pollution contribution.

Environmental aspects, method of approach and evaluation in this thesis will be performed using the comparison of existing data, official emissions from technology for all three alternative fuel solution as well as conventional diesel fuel. WTW results will identify competitiveness of the different powertrains– fuel options.
WTW estimated emission, is an approach to introduce criteria issues which are closely matched with primary energy utilization and environmental impact. WTW emission is a useful tool for decision makers regarding new alternative technologies.

The analysis of fuel efficiency and pollutant emission shows which solution for type of bus engines is the most appropriate to reduce GHG emission and air pollution and shows the advantages of using alternative energy sources. GHG emission considers CO_2 as the most significant representative and air pollution focuses on NO_X and PM as the most significant contributors to the overall situation. The impact of each one is not the same on the environment and harmfulness values are different.

Total GHG emission can be calculated with simplified model, where all influences are included[2,]:

$$GHG_{Total} = GHG_{Manuf} + \sum_{y=1}^{n} GHG_{WTW} \quad (5)$$

$$GHG_{WTW} = GHG_{WTT} + GHG_{TTW} = \left(GHG_{CO2eqWTT} + GHG_{CO2eqTTW}\right) * y * Range \quad (6)$$

$$GHG_{CO2eqWTT} = DK_{eq} l/km * DK_{ed} kWh/l * CO_{2eq}\ g/kWh \tag{7}$$

GHG_{Total}... GHG total by cycle (kg/annual)

y ... Year

GHG_{Manuf} ... GHG generated by bus production (kg/annual)

GHG_{WTW} ... GHG generated by WTW cycle (kg/annual)

GHG_{WTT} ... GHG generated by WTT cycle (kg/km)

GHG_{TTW} ... GHG generated by TTW cycle (kg/km))

$GHG_{CO2eqWTT}$ ... CO_2 emission generated by fuel provision (kg/kWh)

$GHG_{CO2eqTTW}$ ... CO_2 generated by TTW cycle, fuel burning (kg/km)

DK_{eq} ... Diesel fuel (Diesel Kraftstoff) equivalent (l/km)

DK_{ed} ... Diesel fuel (Diesel Kraftstoff) energy density (kWh/l) here $DK_{ed} = 10.4\ ^{kWh}/_{l}$

$Range$ ... Annually range per bus (km)

Diesel fuel energy density is 10.4 kWh/l and this parameter is here used to convert equivalent diesel fuel to appropriate amount of energy (natural gas, hydrogen or electricity).

From complete life cycle of vehicle, the most important for GHG emission and air pollution evaluation are bus manufacturing and WTW cycle. The other steps could be unattended in calculation. For air pollution, the calculation looks the same as for GHG, just instead of CO_2 data, NO_X and PM are analoged. The behavior of emission reducing through time frame will be presented. The amount of NO_X and PM is significantly lower and the unit of emission is interpreted in *kg /annual*.

4 Economic assessment

The economic assessment of the four types of buses will be conducted through costs and benefits analysis of the existing and researched data. The TCO scenario has variables in 4 categories:

- purchase costs (in meaning capital costs: bus manufacturing costs also here vehicle purchase cost)
- required cost of energy and fuel price to calculate transportation costs (here called fuel costs)
- environmental costs (CO_2 tax emission costs) and
- corrective and preventive maintenance and technology replacement costs (here called maintenance costs).

The first analysis will be on the current costs and further analysis will explain each and subsequent cost independently. Based on published data, an economic model will be developed and applied as approximation for future development.

4.1 Current Total Cost of Ownership analysis

All relevant existing input parameters for current costs, which have an affect directly on TCO, will be referenced from existing literature. One evaluation tool for comparison of total costs of conventional buses to alternative powered busses, is TCO that includes all calculations of relevant costs over life duration. It is necessary to identify assumptions of the owner's driving characteristics as one of the limits of TCO. The annual driven distance in km would affect the TCO results, therefore the same distance (km) per bus annually is considered. In mathematical terms, the TCO can be evaluated by using the following equation (1).

Costs will be presented for each type of a bus yearly. This implies the cost of purchase, operation, maintenance, replacement investments (e.g. for a battery change necessary during the lifetime of the bus, FCEB and BEB), cost for fuel consumption and CO_2 cost. A second battery or a second fuel cell is used after seven years of bus usage as an option for electric mobility during the operational service of a life. Significant investment cost reductions are expected for all alternative technologies.

The following paragraphs explain in more detail all inputs for TCO.

4.1.1 Bus purchase costs

A diesel bus is the most common type of a bus used in public transportation. Natural gas buses are becoming more and more a favorable choice to replace diesel buses because of their availability and lower cost. These types of buses usually use compressed natural gas (CNG) as fuel and they will be observed in this study. The specifications of diesel and natural gas buses are similar, (i.e. Curb weight is 10 600 kg, engine power 205kW, transmission is 12-speed automatic gear-box)[10].

The purchase cost corresponds to the initial costs of the buses at the beginning of the service life. For the purposes of this analysis, the infrastructure including charging equipment and fueling stations are considered as fixed costs. As such they are not included in the bus lifecycle cost but to some extent are included in the fuel cost estimates.

The production costs depend to a large degree on the main components of the bus. A simplified breakdown is used to calculate the vehicle production costs. Four vehicle configurations are defined and investigated:

- diesel bus (DB)
- natural gas bus (NGB) run on compressed gas
- the fuel-cell-electric bus (FCEB) run on hydrogen
- the battery-electric bus (BEB) run on electricity from grid.

Integration of new bus technology will not significantly reduce purchase cost of diesel bus. Depending on the uncertainties in the development of future battery technology, the battery system costs is unpredicted. Currently, it is not clear which technology will succeed in terms of bus requirements and production costs. Future purchase costs are difficult to predict, but it is estimated that the battery costs will decrease due to battery volume and new technology development. Battery costs are generally similar for light- and heavy-duty vehicle applications. The specific battery system costs should decrease with increasing battery size. However, based on current significant uncertainties, the battery system cost for light and heavy-duty vehicles as well as for battery-electric vehicles and fuel cell hybrid electric vehicles were assumed to be equivalent[18]. The costs of electric motors are expected to decrease over time due to the volume of production and learning curve effects over time. What certainly increases the price of the vehicle is replacement recommendation of a battery every seven years for battery-electric and fuel-cell-electric bus.

Fuel cell system price varies widely within the available literature. One approach uses dedicated long-life stacks where stack operation is expected to exceed 30 000 hours[19]. The other approach involves bus stacks where shorter warranties will be more likely encouraged, with reduced stack replacement costs. At present, fuel cell system costs are very high mainly due to the limited quantity produced. Additionally, production processes are not automated yet, instead they are carried out manually. This has direct impact on cost increase. Assuming a rise in production, and innovations in production technology, a reduction in platinum used and volume of production, costs per kW are predicted to decrease[19]. Cost development of additionally required systems, which are electrified systems like power electronics, the battery management system, etc., are estimated to decrease over time[9].

For the consideration of four type of buses in this scope, the costs are presented in Table 3. These data are representative for the calendar year 2018 and in the future, these parameters will vary. Diesel and natural gas buses are not subject to significant vehicle price change, but to alternative electric-driven, there are very high expectations. Battery costs and fuel-cells spare parts costs are not presented in the bus purchase cost, rather, they are presented in the table as technology replacement costs. Table 3 and Table 4 show parameters in TCO calculation, $C_{purchase}$ and C_{rep}, in equations (1, 2).

Table 3: Bus purchase cost in 2018 [2]

Year/Type of bus	DB	NG	FCEB	BEB
Vehicle costs (€) 2018 ($C_{purchase}$)	170 000	240 000	1 000 000	313 000

Based on other analyses, similar prices are found for buses in Europe. Dolman and Maden (2018)[21] in their study titled, “Strategies for joint procurement of fuel cell buses”, confirmed that purchase costs for fuel-cell-electric buses was 625 000 euro[21].

The major costs of electric vehicle maintenance are battery/fuel-cell replacement, depending on the life span of the battery and the cost of replacement. Battery costs decrease around 2% annually[10]. Battery capacity for solo buses analyzed in this study is more than 300 kWh. For both types, battery-electric and fuel-cell-electric buses, replacement for the battery and fuel-cell, is suggested to be done every seven years[2].

Table 4: Technology replacement costs for 2018[2]

Year/Type of bus	DB	NG	FCEB	BEB
Technology replacement cost (€) 2018 (C_{rep})	0	0	100 000 (new fuel cell) + 9 000 (2. Battery)	54 000 (new battery)

The battery-electric bus with battery capacity of 396 kWh covers 160 km up to 260 km between refueling, depending on the electrical air conditioning. The bus produce electricity by breaking down and driving downhills[73].

4.1.2 Operating and maintenance costs

Maintenance costs, being part of TCO, depend on multiple variables such as the vehicles age, duty cycle, topography, bus types, fleet maintenance practices, etc. Maintenance costs includes total cost for one bus life duration, scheduled cost and unscheduled cost. Scheduled costs include preventive maintenance based on the OEMs' recommendations. All other maintenance (corrective maintenance) is included in unscheduled costs. The warranty work—which is not included in the analysis—is handled by the OEMs. On one hand, the maintenance costs depend on the personnel costs, with the respective personnel key figures and the average annual salaries for workshop employees, as well as the material costs[20]. The component replacement includes, for instance, the periodical replacement of storage batteries and fuel cell stacks. Maintenance costs include general repairs, diagnostics and spare parts.

The next type of expenses to be considered is:

- Interior and exterior: Includes body, glass, cab and sheet metal, axles, wheels, and drive shaft, tires, seats and doors, and accessory repairs such as hub odometers and radios, lighting
- Propulsion-related systems: Repairs for exhaust, fuel, engine, electric motors, battery modules, propulsion control, non-lighting electrical (charging, cranking and ignition)
- Labor for inspections during preventive maintenance
- Brakes: Includes brake pads, disks, calipers, anti-lock braking system, and brake chambers
- Air system (general): Heating, ventilation and air conditioning, air intake, cooling, and transmission
- Bus insurance policy

Table 5: Maintenance costs[21]

2018	DB	NGB	FCEB	BEB
Bus Maintenance (€/km)	0.18	0.22	0.28	0.28

4.1.3 Fuel costs

Referent year shows fuel consumption cost per km. Using known referent fuel prices derived from fuel costs expressed in €/km. The data for the referent year 2018 is presented in the table below:

Table 6: Fuel costs for 2018[2,10]

2018	Diesel	Natural gas	Hydrogen	Electricity
Fuel consumption pro 100km	43.53 (l)	56.94 (m^3)	9.08 (kg)	155.56 (kWh)
Fuel consumption DK eq (l/100 km)	43.53	56.94	29.97	15.57
Fuel price	1.20 (€/l)	0.78 (€/m^3)	7.50 (€/kg)	0.20 (€/kWh)
Fuel costs (€/km)	0.52	0.37	0.68	0.32

Some studies have confirmed fuel price annual increase which would be used in TCO calculation, i.e. the energy price was assumed to increase annually by about 6%, based on the history of energy price development in the last 10 to 15 years[13]. This calculation is obtained from the average fuel consumption per bus multiplied by the current average price of fuel using Equation 3. This category is variable, because the fuel price varies through time depending on the economy.

Fuel price is not stable and in 2018 tended to increase with time. However, currently due to economic crisis, fuel price has significantly decreased.

Figure 9 shows historical diesel and gas price in the EU. The decrease in 2020 is caused by economy crisis in the world due to the health epidemic.

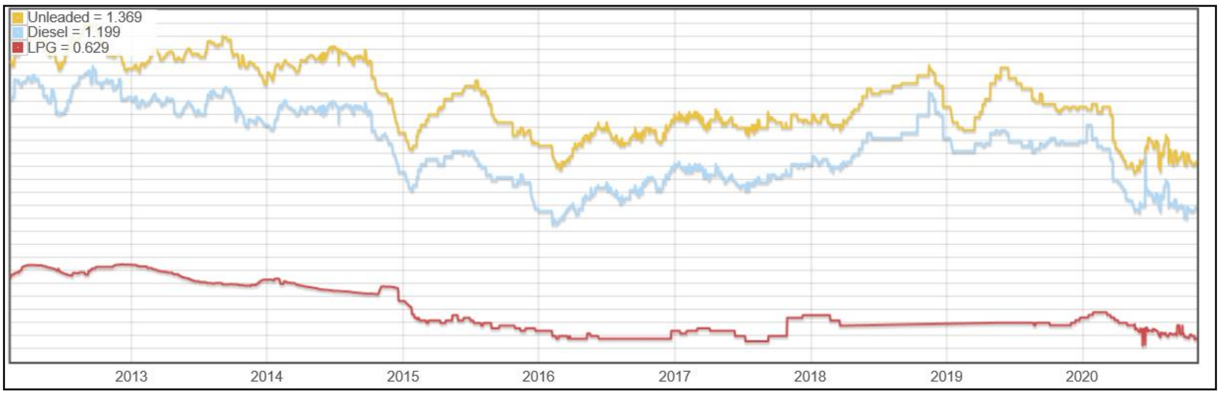

Figure 9: Fuel price statistic in EU 2013-2020 (Source: Wikipedia (2020))[22]

An important input for achieving the results is a discount factor as shown in Table 7, depending on the type of bus. The discount factor is a parameter derived from historical data that reflect cost over time. Discount rate for diesel buses and natural gas buses are taken from general inflation from 1999-2019 and it was 1.4 %[26]. Lajunen and Lipman (2016)[10] analyzed the determinates for newer technology buses like fuel-cell-electric and battery-electric buses, at a 4% discount factor. For alternative buses, more rapid cost decrease is supposed over time because of very high initial costs. In a study by Johnson et al. (2020), 3.6% discount rate is predicted for battery buses from the year 2020.

Table 7: Discount factor for 2018[10, 26]

2018 year	Discount factor (%)
DB	1.4
NGB	1.4
FCEB	4
BEB	4

4.1.4 CO_2 emission costs

The CO_2 emission generated in the full Well-To-Wheel phases of the vehicle fuels is considered. Average CO_2 emission is calculated for each fuel type in Well-To-Tank and Tank-To-Wheel by using the recent literature. The tax price for carbon dioxide is seen as an important tool to achieve the 2°C target, by Paris climate agreements 2015. In order to achieve the Paris targets, CO_2 tax prices must be 32 - 65 €/ton by the year 2020. These will rise to 41- 82 €/ton by the year 2030. The tax price for CO_2 in the year 2018 is considered to be 20 €/ton[22]. With conversion using equation 4, the values for CO_2 tax emission cost for each type of bus are presented in Table 8.

Table 8: CO_2 emission costs in 2018 [2, 22]

	DB	NGB	FCEB	BEB
C_{CO2_y} (€/km)	0.028	0.027	0.024	0.018

4.2 Total costs of ownership

The costs for each year and the accumulated costs for every type of bus over time will be calculated and presented using TCO model. Figure 10 shows high TCO for fuel-cell-electric bus. With purchase costs from the year 2018, the utilization of fuel-cell-electric bus is not still economically justified. From Figure 10, it is clear that battery-electric bus will reach the same accumulated TCO as diesel and natural gas bus over the lifecycle. Seven years of battery and fuel-cell life has a significant increase in TCO, which is graphically clear.

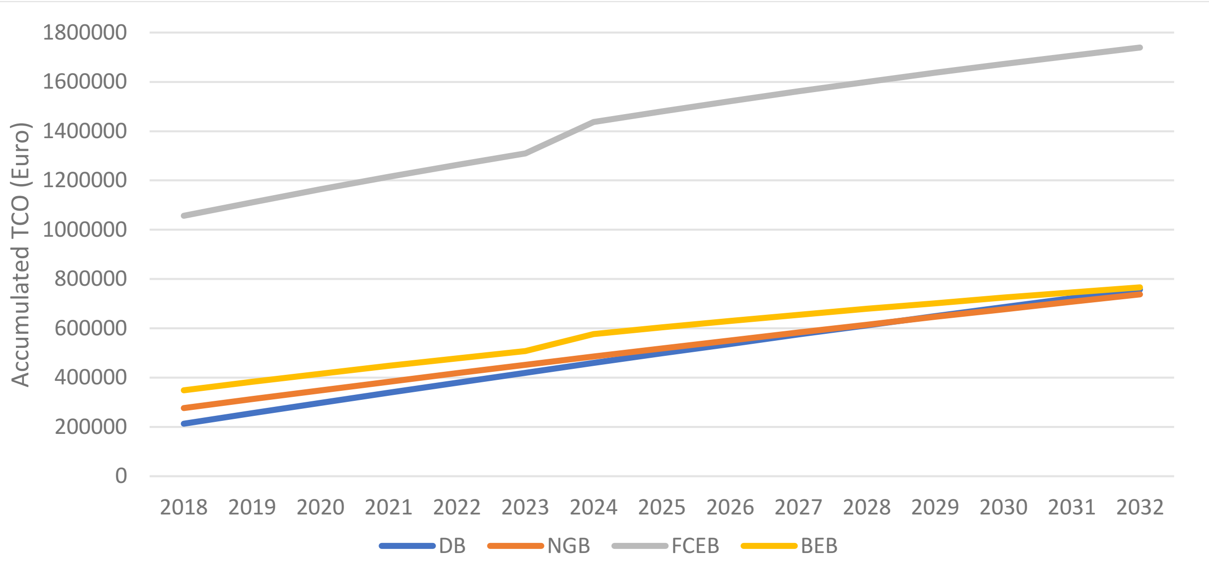

Figure 10: Accumulated TCO from the year 2018 without annually CO_2 costs increasing

Figure 11 presents the TCO for the natural gas, battery-electric and fuel-cell-electric buses as the TCO difference relative to the diesel bus (having a reference value of zero). The results obtained show that natural gas buses will be more cost effective than diesel buses (circa 2029). Battery-electric buses will be competitive with diesel buses after 2032. Because fuel-cell-electric buses are at the present much more expensive, even with the cost reduction in fuel-cell technology and hydrogen price, these would still have significantly higher TCO than diesel buses at the end of their evaluation time. The achieved range and refueling characteristics of battery-electric buses may not be suitable for all bus driving cycles. This means that long distance drivings are not favored. However, currently, the fuel-cell-electric bus is the only solution for zero tailpipe emissions.

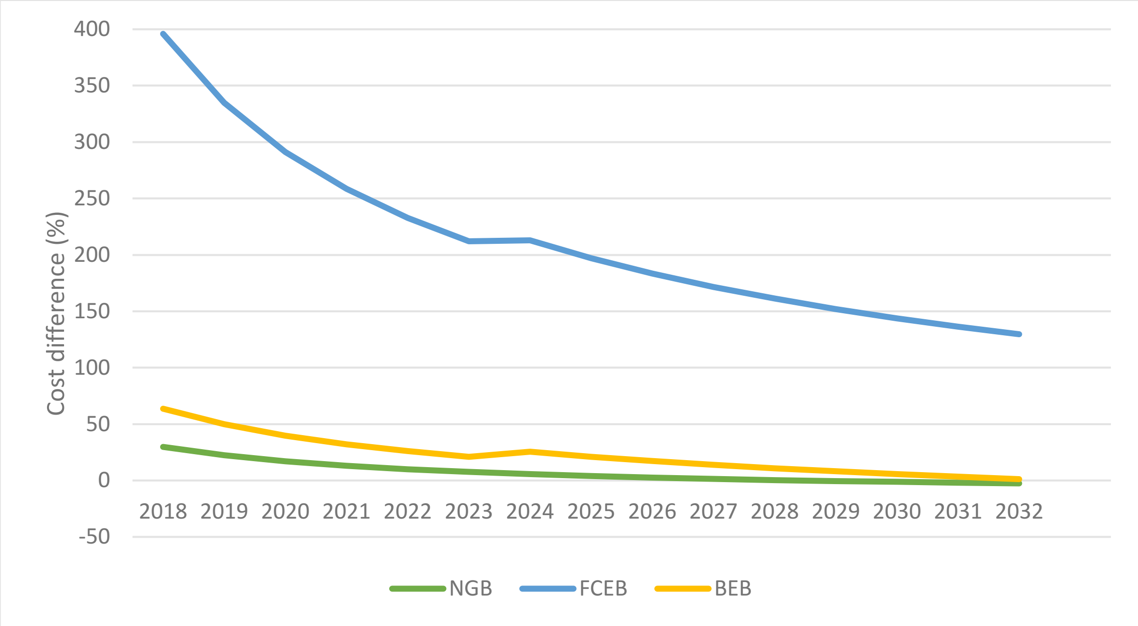

Figure 11: Cost difference of the NGB, FCEB and BEB without annually CO_2 costs increasing from 2018

Figure 12 presents the same results as in Figure 10 but with CO_2 included, increasing the annual tax costs. It is assumed to increase every year by 20%[10] starting from the year 2018. So high increase percentage for CO_2 tax cost is according to the age of engine as well as worldwide CO_2 increasing per year. The results show that CO_2 tax costs have a significant impact on the TCO of fuel-cell-electric and battery-electric buses.

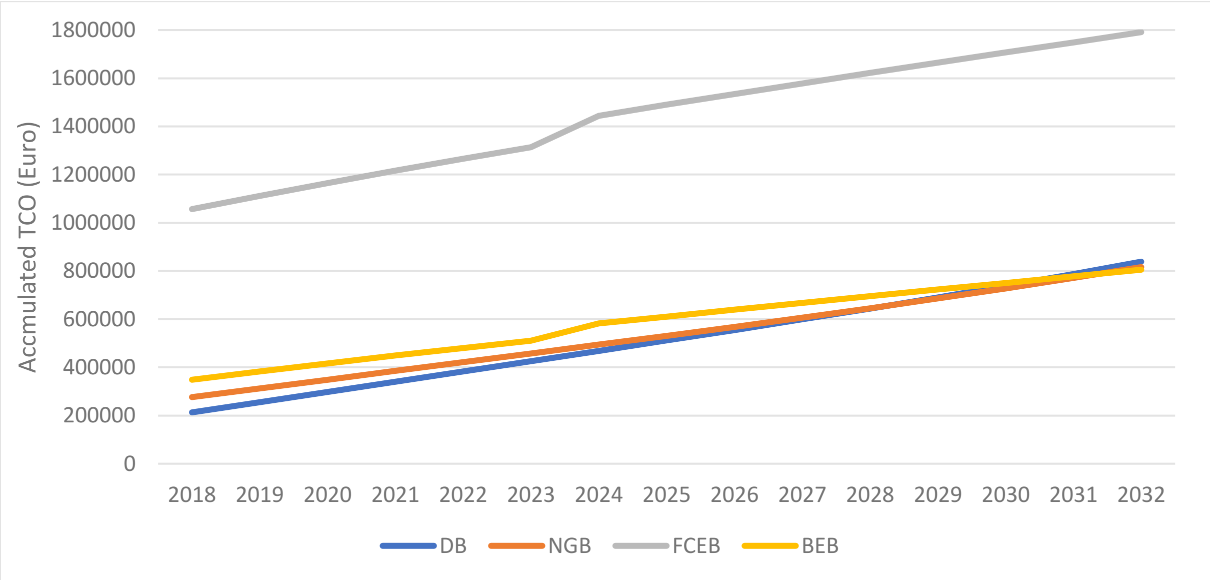

Figure 12: Accumulated TCO from 2018 year with annually CO_2 costs increasing

Including the annual CO_2 tax costs obviously has an impact on TCO. In the year 2027, natural gas bus will be more cost-effective than a diesel bus. In the year 2031, it is expected that battery-electric bus will be more economically preferred than diesel buses. TCO costs in the year 2032 for fuel-cell-electric bus will on average be lower by 20% with CO_2 tax cost increasing than without CO_2 tax cost increasing when compared to TCO for a diesel bus.

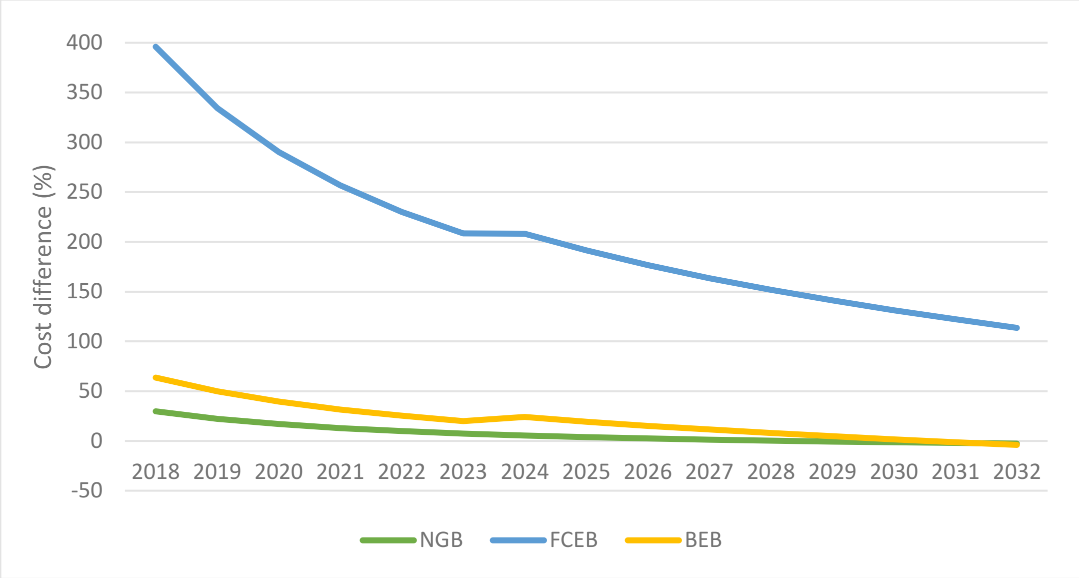

Figure 13: TCO Effectiveness of the NGB, FCEB and BEB with annually CO_2 costs increasing from 2018

Natural gas utilization is increasing. It ranks as one of the most often used alternative fuels for public transportation. After diesel buses, they are most represented in the bus transportation sector in the EU. The purchase costs and maintenance costs for natural gas buses are higher than for diesel buses. Fuel costs could reduce TCO for natural gas buses. This parameter, C_{fuel}, has a strong influence on the financial effectiveness of using natural gas buses instead of diesel buses.

Based on data from 2018 and TCO analysis, fuel-cell-electric buses are not economically viable to be used. Their TCO is still very high. Despite the fact that battery-electric bus has 60% higher initial costs than diesel bus, at the end of their lifespan, the TCO are almost equal. One of the desired outcomes to achieve sustainable development from an economic point of view is using natural gas and battery-electric buses.

4.3 Cost scenarios for buses in the future

In this chapter will be analysed TCO from the year 2030 and up to end of life, fuel prices in 2030 are assumed in Table 9.

Table 9: Fuel costs for 2030[2, 23]

2030	Diesel	Natural gas	Hydrogen	Electricity
Fuel consumption DK eq (l/100 km)	43.53	56.94	29.97	15.57
Fuel price	1.4 (€/l)	1.2 (€/m3)	5 (€/kg)	0.21 (€/kWh)
Fuel costs (€/km)	0.61	0.45	0.45	0.34

Fuel prices for the year 2030 are taken from researched literature and will be used for TCO calculation from the year 2030. On the fuel cell itself, major gains to date have been driven by innovations in technology and product improvements. With years of experience, the EU has been able to deliver these gains in combination with industry leading durability and reliability. Additionally, there are other elements that have contributed to the overall cost reduction of fuel-cell-electric vehicles including: the reduced price of the hydrogen storage tank, reduced price and improved integration of the vehicle's electric powertrain, fuel cell-battery hybridization of the vehicle-combining a smaller fuel-cell with lithium-batteries, whose price has been decreasing. Based on analysis from Jefferies and Göhlich (2020)[26] electricity costs escalation is +3.8% and diesel fuel price increasing +0.7% annually.

Purchase costs for the future in the year 2030 are expected as pictured in the table below. Decreasing of investment costs for battery-electric and fuel-cell-electric buses is expected because of further technical research and development, while maintenance costs will be on the same level as in the year 2018. Pütz (2018)[2] describes the purchase costs for all types of buses for the medium term in the year 2030. The price for diesel buses will be 160 000 €, for natural gas buses slightly higher than in 2018 and amounts to 246 000 € and it presents a 2.5% purchase price increasing from the year 2018. For fuel-cell-electric bus, the purchase price considered is 428 000 € and for opportunity-charger solo, battery-electric bus is 274 000 €. On the other hand, Dolman and Maden (2018)[21] summarized the capital costs for fuel-cell-electric bus to be 320 000 € and battery-electric bus to be 220 000 €.

Table 10: Bus production cost for 2030[2, 21]

Year/Type of bus	DB	NG	FCEB	BEB
Vehicle costs (€) in 2030	160 000	246 000	320 000	220 000

According to the Pütz (2018)[2] study, the price for the new battery and fuel cell in the future would not be changed. This study considered the case with the prices from Table 11, in which the price for battery in 2030 will be around 60 €/kWh[28]. Using the same ratio price, it could be defined that the fuel cell price is reducing. Basically, three main types of configurations exist: buses with a large-size battery of about 320 kWh with overnight depot charging, with a medium-size battery of 180 kWh with opportunity charging at the end of lines and buses with a small-size battery of about 80 kWh with opportunity charging at many bus stops on the street[29]. This table analyzes an electric bus with a large size battery.

Table 11: Technology replacement costs for 2030[28, 29]

Year/Type of bus	DB	NG	FCEB	BEB
Technology replacement cost (€) 2030 (C_{rep})	0	0	40 000 (2. Fuel cell) + 3 500 (2. Battery)	20 000 (2. Battery)

The discount factor for the year 2030 is used to calculate the operating cost of the investments. It has been set to 3%. This is a low discount factor, and a city or government can often borrow at such low rate[24].

Table 12: Discount factor for 2030[24]

2030 year	Discount factor (%)
DB	3
NGB	3
FCEB	3
BEB	3

CO_2 costs from 2030 are calculated based on the average Well-To-Tank GHG emission and the price of 40 €/tonne (own depiction) based on the proposal from Paris climate agreements 2015. Electricity energy consumption is the lowest and the cost for GHG emission for battery-electric bus is the cheapest. CO_2 emission is twice as expensive for diesel conventional bus and natural gas bus as compare to battery-electric buses (Table 13). Graphical presentations of both scenarios illustrated as follows: with constant CO_2 tax price and with annually increasing CO_2 tax price.

Table 13: CO_2 emission costs in 2030[2, 22]

	DB	NGB	FCEB	BEB
C_{CO2_y} (€/km)	0.047	0.044	0.042	0.018

Good O&M practices are necessary to achieve optimal fuel economy and low emissions. O&M practices can reduce significant expenditures on fuel, freeing up resources for improved services. Energy-efficient O&M practices must be carefully planned and must be appropriate for the size, resources, and "culture" of each city bus company in order to be successful. While virtually every bus operator uses a basic checklist to conduct O&M practices, many smaller operators do not have the time or staff to develop instructions for other essential maintenance and repair activities. The transit community has a great deal of collective knowledge concerning practices, and the community can freely exchange this knowledge without the competitive pressures typically found in other industries. Good driving practice should lead to a reduced maintenance costs. Maintenance costs are assumed to remain the same as in the year 2018.

Firstly, the accumulated TCO from the year 2030 for all types of buses without decreasing annual CO_2 costs will be presented. In comparison to the year 2018, significantly lower TCO for fuel-cell-electric buses (in the year 2030, 50% of the accumulated TCO decreased than in the year 2018) should be considered. Based on economic calculations, natural gas buses and battery-electric buses will be competitive against conventional buses.

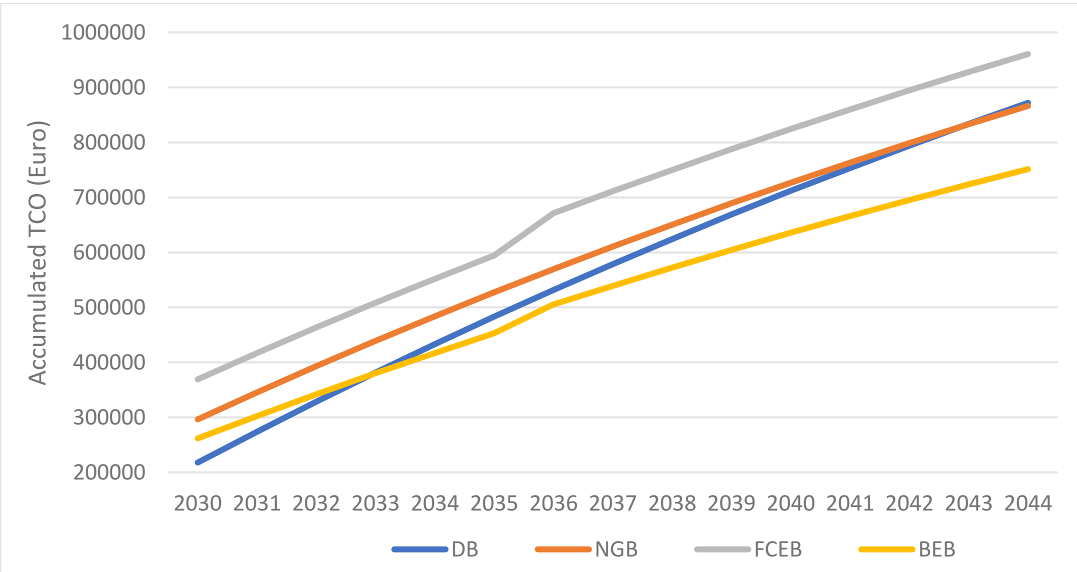

Figure 14: Accumulated TCO from 2030 year without annually CO_2 costs increasing and with battery replacement

Based on technical improvement, battery and fuel cell replacement in the future could be avoided if the battery has more capacity. For buses purchased in the year 2030, purchase costs are significantly lower for battery-electric and fuel-cell-electric buses. Based on accumulated TCO, battery-electric buses will be more cost-effective than diesel buses after 3 years of utilization in the scenario with fixed

CO_2 costs. With natural gas buses, the situation is similar to buses purchased in the year 2018, just at the end of the lifecycle as the operating costs remain the same.

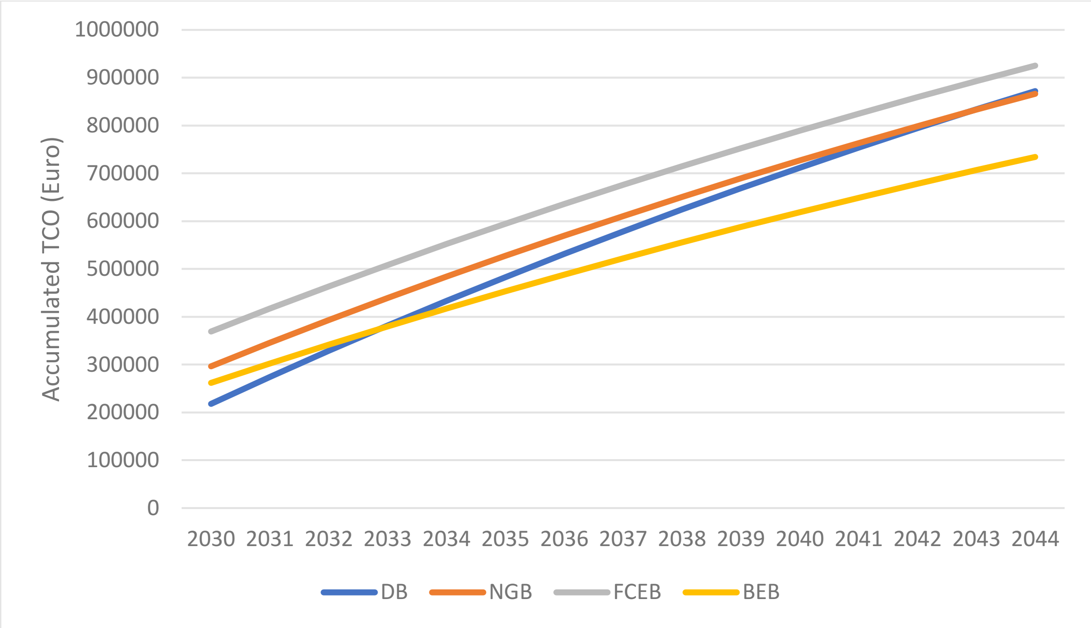

Figure 15: Accumulated TCO from 2030 year without annually CO_2 costs increasing and without battery replacement

The drive system for electric buses is simple compared to a diesel bus with fewer moving parts. Due to simplification, it is expected that the maintenance costs for the electric bus would be less than the conventional diesel bus[25]. The major cost of battery-electric and fuel-cell-electric buses are the battery and fuel-cell replacements, depending on the lifespan of the battery and the cost of replacement. The lifespan of a battery is the number of cycles of discharge and charge which is an important factor. The price of the battery in 2018 was around 130 Euro per kWh. The estimated price in 2030 is 50 Euro per kWh[28].

Scenario with annually CO_2 tax emission increasing and with battery replacement is shown in Figure 16. TCO is higher for all types of buses. It is considered that after three years of battery-electric buses utilization, TCO will be lower than that of diesel buses. At the end of the bus lifespan, fuel-cell-electric is more cost-effective than diesel bus. It considers the statements, that in this scenario, it will be economic justified after the year 2030 to buy and use fuel-cell-electric bus than the conventional bus.

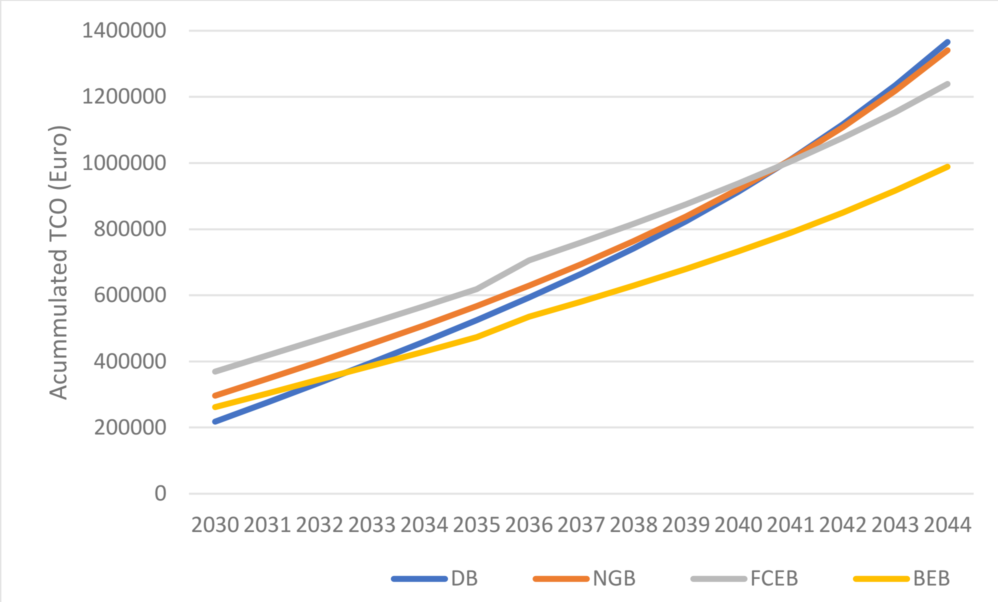

Figure 16: Accumulated TCO from 2030 year with annually CO_2 costs increasing and with battery replacement

The scenario with CO_2 costs increasing and without battery replacement in the future is presented in Figure 17. Escalation of TCO for diesel buses and natural gas bus is expected because of very high costs of CO_2 and constant yearly increase. In this scenario, the lowest TCO has battery-electric bus. Despite higher installation costs for battery-electric bus, overall accumulated TCO is lower than for conventional buses or natural gas buses.

With annual CO_2 tax emission costs increasing, could be clearly deducted that battery-electric bus will after four years of utilization be competitive with conventional bus, fuel-cell-electric bus after nine years and natural gas after ten years.

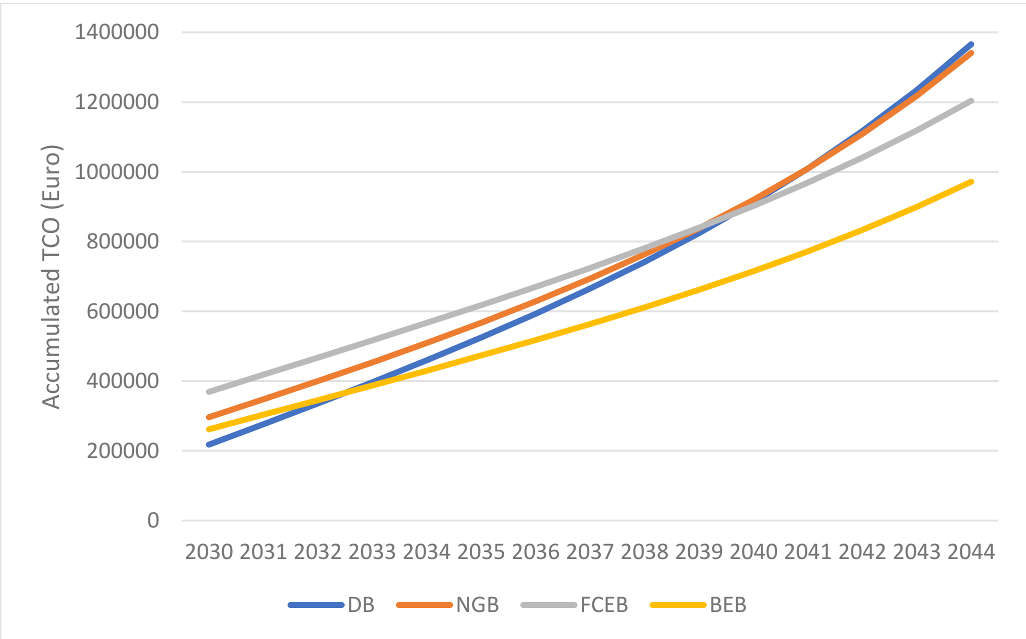

Figure 17: Accumulated TCO from 2030 year with annually CO_2 costs increasing and without battery replacement

Some of the highlights could be derived from this scenario:

- For diesel bus, there is no expectation for purchase price reduction. Forecast for diesel fuel is difficult to determine due to political issues. To make diesel buses more competitive in the market, maintenance cost should be reduced. Therefore, the future predictions remain mostly unchanged.
- Evaluation for natural gas buses is similar to conventional buses. The cost optimization will be reflected through maintenance reduction and through purchase price. Variation in fuel price has strong influence. There are no changed advantages in the future.
- Fuel-cell-electric bus presents the best life-cost reduction in percentage. Purchase price will be significantly decreased, while there is visible reduction in bus maintenance.
- Focus on battery-electric bus is on reduction of purchase price. Forecast for electricity price in the future could be presented as increasing function. But one of the favorite solutions in future alternative bus transportation should be battery-electric bus, because TCO for battery-electric bus is still lower than TCO for fuel-cell-electric bus.
- It could be concluded from economic point of view that the solution for bus transportation in the future surely will be alternative type of buses.

5 Greenhouse gas emissions

An essential factor for achieving sustainable development is the availability of alternative fuels for bus transportation means using renewable energy. Alternative type of buses demand is increasing and natural gas ranks nowadays as one of the most often consumed alternative fuels for bus transportation[33]. However, there are necessity to improve air quality in urban areas, enabling cleaner production in the transportation sector. Replacing diesel buses with other alternative types in urban transportation reduces the emission of toxic substances and GHG and decreases the negative impacts from the transportation sector.

5.1 GHG emissions in the EU: State of the art

Regarding data from the year 2020, the transportation sector is one of the largest GHG emission contributors in Europe. Figure 18 presents situation of GHG share in EU in 2020. Cars, trucks, commercial aircrafts, railroads, buses all contribute to transportation end-use sector emissions.

GHG emission need to fall by around two thirds by the year 2050, compared to the year 1990 levels, in order to meet the long-term 60% GHG emission reduction target[34]. The purchased buses today will be normally run for around 14 years. This directly means that if buses run on fossil fuels are not quickly phased out, it will take a long time before GHG emission can be reduced.

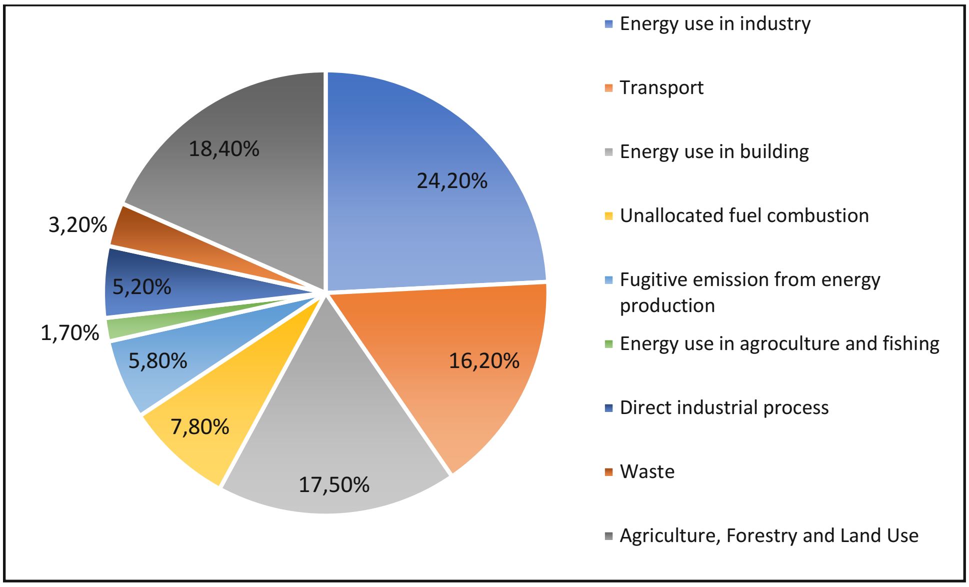

Figure 18: Share of GHG emission by sector (%) (Source: Our World in Data (2020)) [77]

Figure 18 presents the share of GHG emission by sector in the EU from the year 2020. In the 2020, public transportation was responsible for almost 16.2% of total GHG emissions from transportation (including international aviation and international shipping). Share of global GHG emission per sector could be roughly divided into energy (electricity, heat and transport) 73.2%; industrial processes 5.2%; waste 3.2%; agriculture, forestry and land use 18.4%. Figure 19 shows GHG emission in transportation sector regarding source.

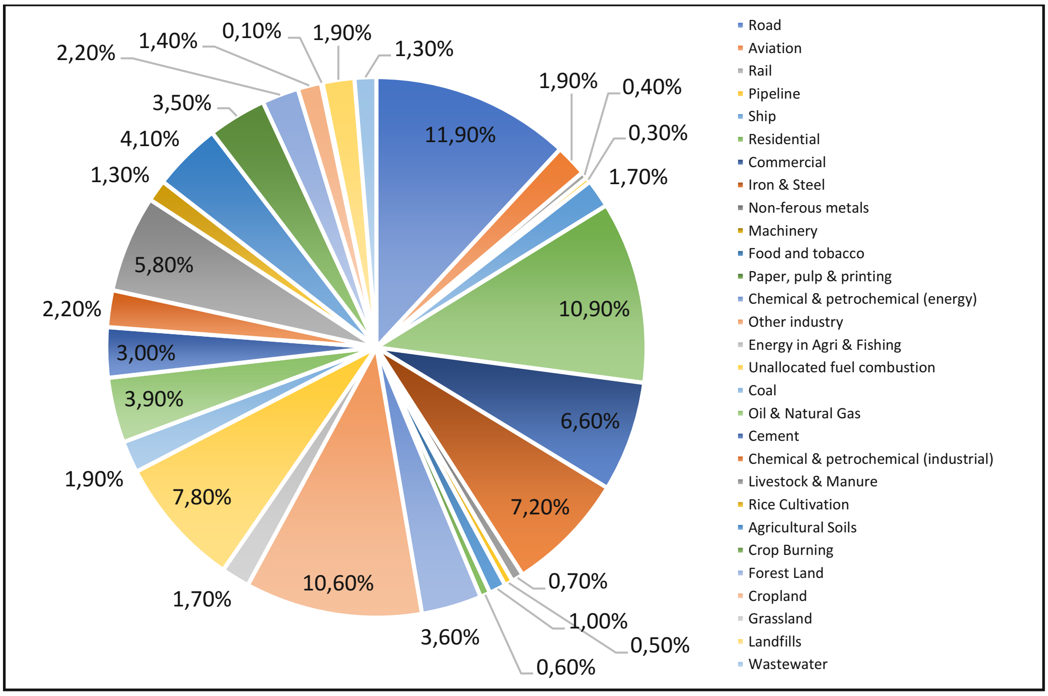

Figure 19: Transportation Sector GHG Emission by Source (%) (Source: Our World in Data (2020)) [77]

As the transportation is the great contributor of GHG emission in the EU, some actions for improving the situation have been identified by the World Resource Institutes (2020)[77]. The second is faster deployment of low emission alternative energy for transportation such as electricity and hydrogen. The EU should direct and accelerate transition to zero emission vehicles and low emission vehicles.

The local authorities and urban cities should invest effort in delivering and applying this strategy. They should promote all benefits for public transportation based on renewable energy and implement incentives for low emission alternative energies and vehicles.

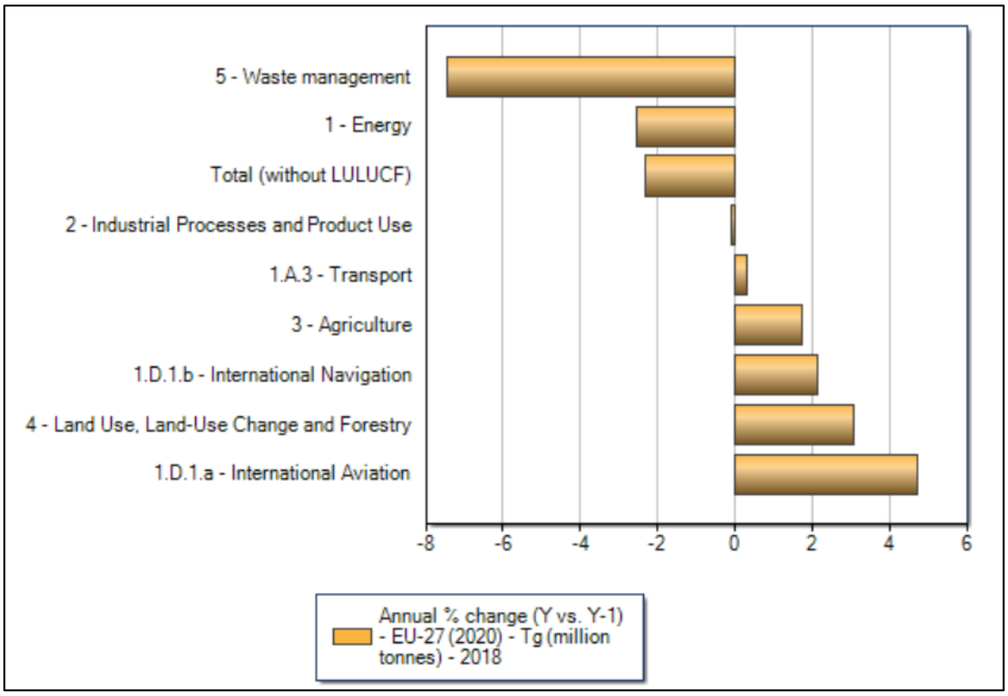

Figure 20: CO_2 change in emission by sector in 2017-2018 (Source: European Environmental Agency (2021))[67]

Figure 20 presents the change in CO_2 emission by sector between the year 2017 and 2018 . Obviously, transportation sector shows minimal progress to reduced emission.

An opportunity to reduce CO_2 equivalent emissions in bus traffic in many countries could be achieved through switching from internal combustion engine buses (ICEBs) to battery-electric buses. Battery-electric buses have better energy conversion efficiency from energy storage to wheel (tank-to-wheel [TTW]) and zero tailpipe emissions. But is not the same situation by vehicle production and electricity generation (well-to-tank [WTT]), where certain amount of emission is produced and there is no significant improvement for reduction. The CO_2 intensity of electricity generation varies based on the sources of energy in the electricity mix of each country and time of day.

The Europe 2020 strategy set the aim for the share of transportation fuels that come from renewable sources. The target in 2020 is 10%. Calculations are made in accordance with the Directive 2009/28/EC on the promotion of the use of energy from renewable sources. In 2016 in the EU had Sweden and Austria as the higher share of alternative buses. Sweden (30.3% of renewable fuel energy used in transportation) and Austria (10.6%) were the only two Member States to reach the target of using 10% of renewable fuel energy for transportation. While France (8.9%) and Finland (8.4%) were relatively close to achieving the target, most of the other EU Member States were around the half-way point to meeting the 2020 objective. With a use of less than 3% of energy from renewables in transport, Estonia (0.4%), Croatia (1.3%), Greece (1.4%) and Slovenia (1.6%), followed by Cyprus (2.7%) and Latvia (2.8%) were significant under the 10% target [32]. The EU had the share of energy from renewable sources in transport to be 7.1% in 2016, compared to 6.6% in 2015 and 1.4% in 2004[32].

In the EU Public buses with batteries, natural gas and fuel cell now present just 3.2 % of the total bus fleet, although extensive marketing measures may give a different impression. Meanwhile, the 2nd and 3rd generation Li-ion technology will be used continually. Ion technology, which is expected to be introduced after 2030/2035, should lead to significant increases in efficiency. Alternative drive technologies should happen parallel to conventional drives in the EU public transportation. Battery-electric and fuel-cell-electric bus utilizations are still very limited till date. If alternative technologies are ready for series manufacturing, the use of these new technologies will be further accelerated in the future. Small and medium-sized transportation companies with a fleet size of less than 200 buses are likely to benefit from the wide use of alternative drives.

An important environmentally relevant advantage of all electric bus concepts is the reduced noise emissions compared to internal combustion engine drives. So, electric buses have a sound pressure level reduced by around 5 dB (A) when compared to diesel buses. Natural gas buses have a pressure sound level reduced by 2 dB (A) when compared to diesel buses [37].

Overnight charger battery buses, which have battery capacities of over 300 kWh in the solo bus, have lower passenger capacities than conventional buses with an internal combustion engine due to the large battery weights. This means that two battery buses should be used to replace a conventional bus in the morning peak. Furthermore, in winter and summer, when forced heating energy or energy to operate the air conditioning system should be supplied from the limited energy capacity of the battery, the required daily driving distance of more than 300 km is not achieved. Refueling time for diesel bus is shorter than for natural gas bus. Short refueling time is for fuel-cell-electric bus, less than 10 minutes[37]. As expected, overnight-charger buses need the longest refueling time.

5.2 Greenhouse gases emissions from fuel

In order to reduce climate change and the environmental impacts of fossil fuels, the role of electric buses in public sector is very important. A detailed review of various performance features for two categories of electrical buses are provided: fuel-cell and battery. The selection process of electric technology is highly sensitive to operational context and energy profile. It highlights that hybrid buses will not provide a significant reduction in GHG and would be suitable for short-term objectives as a stepping-stone to full electrification of transit [38]. Battery-electric buses and fuel-cell-electric buses are capable to satisfying the current operational requirements, but initial investment is the major barrier. Overnight battery-electric bus is advocated as the most suitable alternative bus for transportation context given the expected improvements in battery technology and the trend to utilize sustainable sources in electricity generation.

Initiatives to reduce emissions and instability in oil prices are causing policy makers to implement alternative technologies that will replace oil transit vehicles. Different technological solutions have been operationalized in recent years. Oil-based mobility still holds the huge part in the transportation market and the market penetration of alternative technologies is very small. The implementation of new alternatives for bus transportation depends on the following factors (but not limited to these): energy logistic, cost-benefit, assessment, infrastructure and public acceptance.

Within all these, public transportation offers potential for market penetration of alternatives technologies, especially for bus city transportation. Bus transit provides fixed routes, centralized depot locations and the infrastructures are suitable for alternative technologies. To achieve significant reduction of pollution, the technology could be operationalized, tested and optimized. Selecting a suitable bus for each context depends on various factors such as cost, network, structure, energy source and driving conditions.

Greenhouse gas emissions and pollution in cities are generated mostly by transportation sector. 28% of the overall global energy consumption and the emitted 8.7 gigatons of CO_2 (2012) are from the transportation sector, with annual increase of 2% since 2000 by International Energy Agency (IEA, 2015)[78]. In the second scenario (IEA, 2015)[78], the sector's emissions would need to be reduced to 5.7 gigatons of CO_2 by 2050.

5.2.1 Well-To-Tank GHG emissions

Well-To-Tank present quantified measures of GHG emissions during energy production and distribution. The assessment should be done through the identification of energy production methods, feedstock and the distribution pathways. Due to the significant variation in energy production methods (i.e. fossil fuel, renewable and biofuel) and distribution pathways (i.e. road, rail, pipelines and on site) several models have been developed to calculate the WTT GHG emission.

The WTT emissions include the emissions from the power plants for producing electricity themselves and the emissions from the provision of the energy (sources coal, natural gas, oil and biomass, wind, solar energy).

A Well-to-Tank emissions factor, also known as upstream or indirect emissions, is an average of all the GHG emissions released into the atmosphere from the production, processing and delivery of a fuel or energy vector. In Table 14 is presented, the change in WTT conversion factor which shows lower emission by producing electricity and diesel fuel from the year 2019 to 2020. A hydrogen fuel cell combines hydrogen with oxygen, producing water. This process generates electricity, which powers the electric motor that drives the vehicle. The only emission from a fuel cell bus is water, which forms a vapor cloud as it leaves the exhaust and enters the atmosphere.

Table 14: Well-to-Tank conversion factors[39, 37]

Liquid fuels	% change from 2019-2020
Diesel	-1
LNG	0
Hydrogen	/
Electricity (Grid)	-10

Hydrogen can be used as a low-carbon fuel source. Difference in WTW factors comes from different processes of hydrogen production. Hydrogen can be combusted directly, or it can be used in a fuel cell to produce electricity. Hydrogen can be produces from the pyrolysis (decomposition of methane). Hydrogen from methane decomposition still causes significant GHG emissions between 43 and 97 g CO_2 eq/MJ. Classical steam methane reforming produces 99 g CO_2 eq/MJ. Over 95% of the world's hydrogen is produced using the steam methane reforming process (SMR).

Diesel fuel is usually provided based on a mix of conventional crude oil (dominant today), unconventional crude oil, coal (coal-to-liquid) and natural gas (gas-to-liquid). The supply of natural gas is usually based on a mixture of different countries of origin. A modeling of natural gas upstream chain which mean production, processing and transport, has influence on WTT emission factors. The supply of natural gas from Russia and Qatar has the highest greenhouse gas emissions, while that from the

Netherlands, Norway, Great Britain and Germany is comparatively low[2]. The local and global GHG emission of natural gas for EU depends on ingredients of liquid natural gas, so expected in the future is reduced GHG emission based on biogas.

A mix of natural gas steam reforming (dominant today) and electrolysis with renewable electricity is used to provide compressed hydrogen (compressed gases H_2, CGH_2). In both cases, it is assumed that the hydrogen is produced on site at the petrol station, since a central, large-scale electrolysis infrastructure is not available and required an immense investment that only federal politics can initiate by strategic decision. This is an ongoing discussion because of financial assets distribution. In the case of hydrogen from natural gas steam reforming, the electricity is used to operate auxiliary units (compressors, fans and control for the reforming system and to operate the CGH_2 filling station) from the power grid (low-voltage level). The composition of the German electricity mix 2018 is based on information from the AG Energy balance (2015), based on the Federal Association for Renewable Energies (2015) and the Fraunhofer Institute for Solar Energy Systems (2015)[2], which were extrapolated to the full year. The emissions include both, the emission from the power plants and the emissions from the provision of the energy sources coal, natural gas, oil and biomass. The efficiency of the electrolysis system including the fine purification of the hydrogen is around 60% based on the lower calorific value (corresponding to a power consumption of around 5 kWh per Nm^3 hydrogen)[3]. In the case of hydrogen from water electrolysis, the CGH_2 filling station including the electrolyze is connected to the medium-voltage network. The generation of "regenerative or green" hydrogen and its use are politically propagated. At the CEP (Clean Energy Partnership) filling stations, at least half of the hydrogen should come from renewable energy sources, so that by 2030 50% of the hydrogen will be generated from electrolysis. However, it is questionable whether this quota will be reached in the medium term despite the requirements. Table 15 shows the percentage of hydrogen origin in the year 2018 and 2030.

Table 15: Origin of hydrogen[2]

Row material resource	2018	2030
LNG	80%	50%
Renewable energy	20%	50%

Table 16 presents the amount of CO_2 eq. expressed in g/kWh, which is needed for calculation of total GHG emission.

Table 16: WTT CO_2 Emission of fuels for 2018[2]

Fuel	$GHG_{CO2eqWTT}(\frac{g}{KWh})$
Diesel	57.8
LNG	28.6
Hydrogen	380.8
Electricity	354.7

5.2.2 Tank-To-Wheel GHG emissions

TTW is emission from energy conversion / combustion within the vehicle. A summary diagram showing the results for TTW CO_2 equivalent emission and energy consumption including the evaluation of error bars is present below (Figure 21).

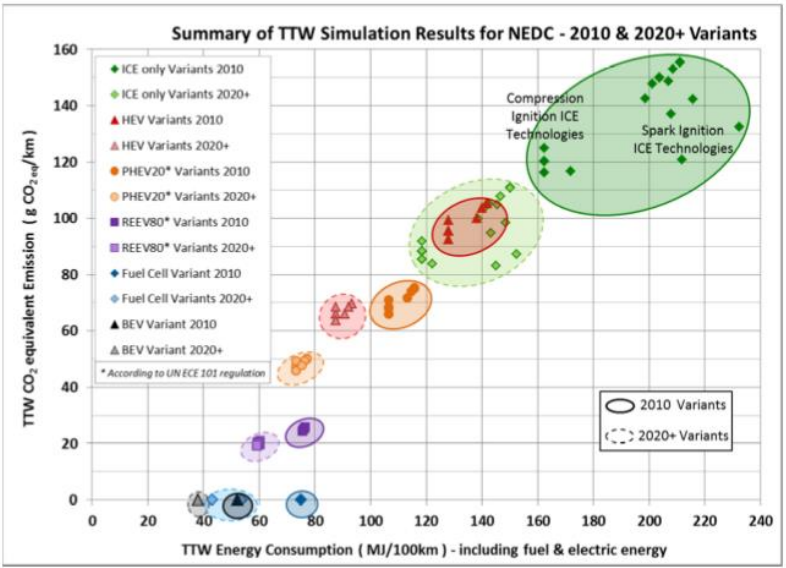

Figure 21: Summary of TTW Simulation Results for New European Driving Cycle (NEDC) (Source: TANK-TO-WHEELS Report (2014))[41]

TTW assessment of GHG emissions estimates the local emissions produced during bus operation. Aspects such as driving condition, congestion, average speed, and the number of stops have huge impacts on TTW.

The following considers the energy consumption and emissions from driving, including the energy consumption for heating / air conditioning for 2018. A newer technology of vehicle has direct influence on lower emission and in the future, is expected to bring about a significant reduction of TTW emission for diesel and natural gas bus. The first column presents analog consumption of diesel fuel, natural gas, hydrogen and electricity. The second column expresses these consumptions in diesel fuel equivalent, it means how much equivalent diesel fuel would be consumed.

Table 17: Consumption, TTW GHG emission and air pollutants of solo buses in operation in 2018, derived from practical measurements, standardized to 16.7 km/h (average)[2, 41, 42]

	Fuel consumption	Consumption DK_{eq}l/100km	$GHG_{CO2eqTTW}(\frac{kg}{km})$
Diesel	**43.53 l/100 km**	**43.53**	**1.15**
LNG	**36.37 kg/100 km**	**56.94**	**1.18**
Hydrogen	**9kg/100km**	**30**	**0**
Electricity	**184.5 kWh/100 km**	**15.56**	**0**

Variations of speed for Medium Duty vehicles from 20km/h to 40km/h can result in a 21% increase in fuel consumption[43]. T Analyzed are city buses with determined number of stops, speed and driving distance. Based on that, fuel consumption expressed in Table 14 is relevant for calculation in this study.

One electro bus in comparison with diesel bus produces around 800 t CO_2 per year[73].

5.2.3 Well-To-Wheel GHG emissions

Standard diesel bus contributes an estimated emission of 1.244 $kgCO_2e/km$ while efficient diesel bus (as micro-hybrid) has an estimated GHG emission of 1.123 gCO_2/km with reduction of 10% in comparison with standard DB.

LNGB's consume in average 50% more energy as standard DB and the estimated GHG emission is 1.398 $kgCO_2e/km$, which means 12% increase of emission in comparison with standard diesel bus.

GHG from hydrogen fuel-cell-electric bus are highly dependent on the method of hydrogen production. If hydrogen is produced using steam methane reforming, the estimated GHG emission would be 689 gCO_2/km, a 45% lower emission than a standard diesel bus.

Large reduction in energy consumption provides the electrification of buses. Using a 2018 electricity grid emission factor, a battery-electric bus estimated GHG emission is 448 gCO_2/km, even 64% lower than a standard diesel bus[44].

The EU is expected to require mandatory GHG certification for bus transportation starting from 2018. Considering this start date, bus transportation CO_2 standards are assumed to require 3% annual improvements from 2020 to 2030. This assumption translates to a 26% reduction in CO_2 from new bus transportation over the period 2020 to 2030[45].

5.3 Energy efficiency

Electrical buses operate with different sources of energy. Electricity for battery-electric bus, hydrogen for FCEB and fossil/biofuel for hybrid electro bus have influence on the performance and the characteristics of electric buses. Each source has self-characteristic to make change on GHG emission at the end effect. These characteristics mean: energy generation, energy storage and energy consumption. These are considered as crucial criteria for optimizing the performance of electric buses as they provide a clear indication on the overall energy efficiency.

Energy efficiency is often determined as the volume of energy required per one Km travel. Energy efficiency for each type of bus will be observed here based on Well-to-Wheel (WTW) assessment. WTW energy efficiency integrates two stages: Well-to-Tank (WTT) that include energy generation, delivery pathway and energy storage and otherwise Tank-to-Wheel (TTW) that include energy utilization for traction power.

5.3.1 WTW energy efficiency

There are different energy production methods; based on that also, the efficiency of electricity varies depending on it. Explanation is pictured below. Production with renewable energy is considered the ultimate method with 100% efficiency.

The Natural Gas Combined Cycle (NGCC) and Coal Steam Cycle (CSC) production methods provide an average of 50% efficiency. Mixed method production contributes to an average of 40% efficiency which is a common production in Europe[20].

It could be also interesting to analyze hydrogen impact on environment. Hydrogen is produced using different technologies that include: renewable energy (electrolysis), natural gas steam reforming (NGSR), gasoline steam reforming (GSR) and coal (gasification). Hydrogen is also produced on-board through an Auto Thermal Reforming (ATR) method. Conclusion could also be that the efficiency of hydrogen depends on both the production method and the delivery pathway. On-board ATR is identified as the most efficient hydrogen production method as detailed below, while NGSR is the most efficient fossil fuel-based hydrogen production method and nowadays produces 75% of world hydrogen consumption.

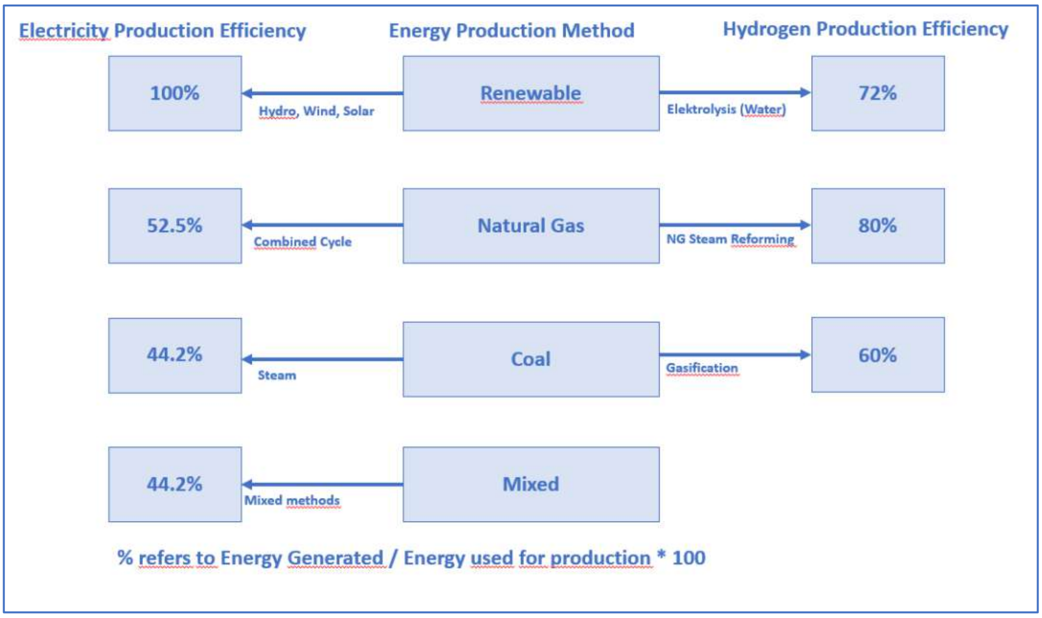

Figure 22: Production efficiency of electricity and hydrogen (Source: Mahmoud et al. (2016))[9]

WTT energy efficiency is clearly calculated based on the ratio between the amount of produced energy to the consumed energy during the process. Megajoule (MJ) of fuel is the official unit for the WTT emission. The most efficient and desired is electricity based on renewable energy, especially when considering natural resources and energy security aspects.

TTW energy consumption varies significantly due to driving conditions like congestion, geography, number of stops, and on the other side propulsion configurations as the degree of hybridization, battery type and fuel cell type. Different rates of energy consumption for the same technology are because of different operational contexts. TTW energy consumption is often expressed in the form of diesel equivalent mile per gallon (mpg) or mega joules for each km (MJ/km).

WTW energy efficiency is calculated based on the combination of WTT and TTW stages, often is described as energy economy. Several tests show varied results for WTW energy consumption/efficiency due to energy pathway and energy generation method.

The table below provides information about WTW energy consumption for diesel, fuel cell and battery powertrains. It is considered that BEB provides the best results for energy efficiency alternative for electrical buses with energy consumption of 10.33 MJ/km. With EU mixed energy sources, the BEB consumes an average of 18.66 MJ/km. Natural gas vehicles have relatively small benefit or even small negative impact, reported in relation to DB. Natural gas is a non-renewable, fossil fuel and WTW CO_2eq emission are not significantly better or can be worse. High potent for WTW CO_2eq savings, almost 100%, have BEB and FCEB.

Table 18: WTW energy consumption [9, 44]

Powertrains	Energy source	WTT (MJ/km)	TTW (MJ/km)	WTW (MJ/km)	Average % reduction of energy consumption relative to DB
DB	Diesel	3.82	16.84	20.66	n/a
LNGB	Gas	4.35	17.05	21.40	3.58%
FCEB	H2 Central NGSR	7.00	10.48	17.48	15.39%
BEB	EU Mix	11.9	6.76	18.66	9.68%
BEB	EU Renewable	3.57	6.76	10.33	50.00%

5.4 Vehicle manufacturing emissions

To determine the environmental impact of bus manufacturing, data for solo buses with different drive technologies are used. Based on the provided information, the data relate to an operational useful life of the first operator of 14 years. For 2030, no changes are assumed for the base vehicle and the different drive variants due to production structures that have been optimized over many years. Any migrations to “purpose design” electric vehicles, which the author considers to be useful, are not considered here due to the unpredictable nature, as this would require a fundamental change in the manufacturing structures. The CO_2 emissions specified in the used literature for one kilowatt hour of Li-ion battery capacity vary considerably, so that the pessimistic value from the study by the Swedish Energy Agency of 175 kg CO_2 / kWh, which apparently applies to batteries from the manufacturer Tesla, is not taken into account here. For comparison, the IFEU Institute in 2016 gives values of 125 kg CO_2 / kWh, which are considered here [2]. It’s expressed in kg by one bus produced.

Table 19: Annual emissions for the vehicle manufacturing subsystem[2]

	GHG_{Manuf} (kg)
DB	2547.2
LNGB	3034.6
FCEB	4552.0
BEB	2812.1

5.5 Current GHG emissions of buses

Firstly, the current scenario will be presented based on data from 2018. This is Followed by estimated data for 2030 and 2050 which will be illustrated scenarios in the future. A baseline Business as Usual (BAU) scenario was developed to estimate the potential evolution of fuel consumption and GHG of heavy-duty vehicles, including buses[43]. BAU assumptions include natural development of powertrain and vehicle-based efficiency improvements. The BAU scenario for the future indicates energy consumption and GHG emission increase without further actions. Heavy-duty vehicles could be liable to 90% increased GHG emission from 2011 to 2030.

The most important GHG contributors are produced by Fuel (WTT and TTW) and for bus production itself. Using equations (2), the total GHG emission generated with bus manufacturing and fuel producing and consuming is presented in Table 20 for the relevant year 2018. Emission during maintenance and disposal is neglected here.

Table 20: Final GHG Emission in year 2018

CO2 Emission	DB	LNGB	FCEB	BEB
GHG_{WTW} (kg/km)	1.411	1.349	1.186	0.944
GHG_{Manuf}[4] (kg)	2 547.2	3 034.6	4 552	2 812.2

Graphically presented are: one DB, one LNG, one FCEB and one BEB accumulated GHG emission through the years. All referent final data are calculated with an approximated velocity of city bus 16.7km/h and daily driven distance of 165km, which means 60000 km annually. With the assumption that bought and produced vehicle in the 2018 calendar year and used in a duration of 14 operational years (it means until 2032).

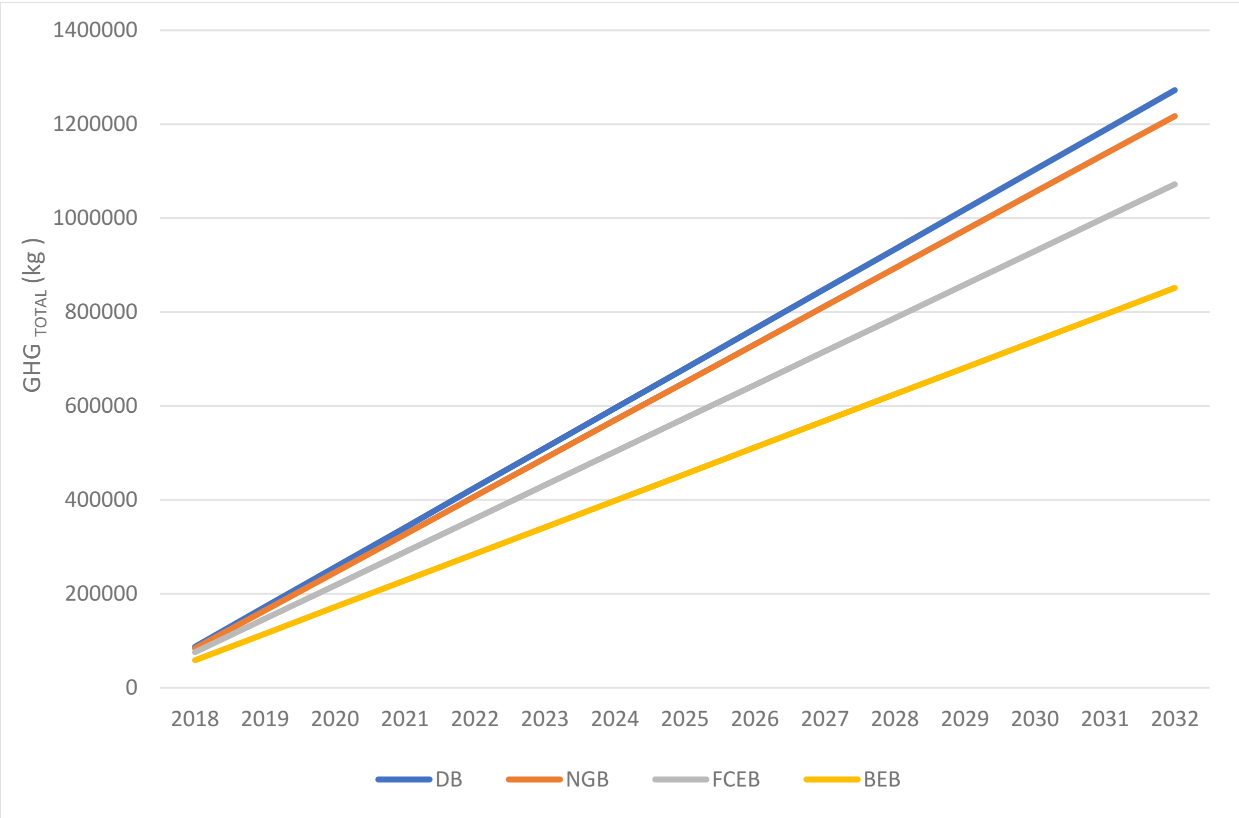

Figure 23: Accumulated GHG emission per year, from 2018

The lowest accumulated GHG emission in 14 operational years has battery-electric (850t CO_2), then fuel-cell-electric buses with total emissions in 14 years (1070t CO_2). The higher emission produces diesel buses (1270t CO_2) and natural gas buses (1217t CO_2).
It is expected that by the year 2030, 40% of CO_2 reduction is the target for cars and bus and 30% is the target for trucks, from the referent year 2018[46]. Within these standards, the electrification of road

transportation is encouraged to ensure the eventual full decarbonization of the sector. If emissions are to be reduced significantly and effectively by 2050, policy makers and industry must focus more on mid-term goals. Existing goals for 2030 and 2040 must be increased considerably if Germany is to make a meaningful contribution to climate protection. Emissions should be reduced by 95% by 2050 for electric vehicles[47].

This is an ambitious goal. Since some sectors of the economy are unable to avoid a proportion of their greenhouse gas emissions, the transportation sector must become greenhouse gas-neutral by 2050 and reduce their emissions to zero. Under all these assumptions, using the described calculation for GHG emission, prediction will be made up to the year 2030. Each year will include emissions produced by bus production and emission produced by bus operation (WTW emissions). Emission during bus production will be the same in the future like in 2018 year. Bus disposal emission as well as emission during maintenance could be neglected.

There are analyzed city buses with a lot of stops and average speed 16.7 km/h. Pollution of all types are a direct function of vehicle-km traveled. Figure 27 shows CO_2, PM and NO_X pollutants all tend to decrease as traffic speed approaches the 40-60 km/h range and then increase again at higher speeds[48]. Avoiding a lot of stop-and-go provides better air quality. Average speed has a great impact on emission for all types of vehicles. Catalyst vehicles show the highest dependences on acceleration: air pollutant emissions increase by approximately 10 to 30% when the acceleration increases at 40km/h. For the diesel conventional vehicles, air pollutant emissions increase slightly by about 5 to 7% when the acceleration level increases from 0.2 to 0.6 m/s^2 [50].

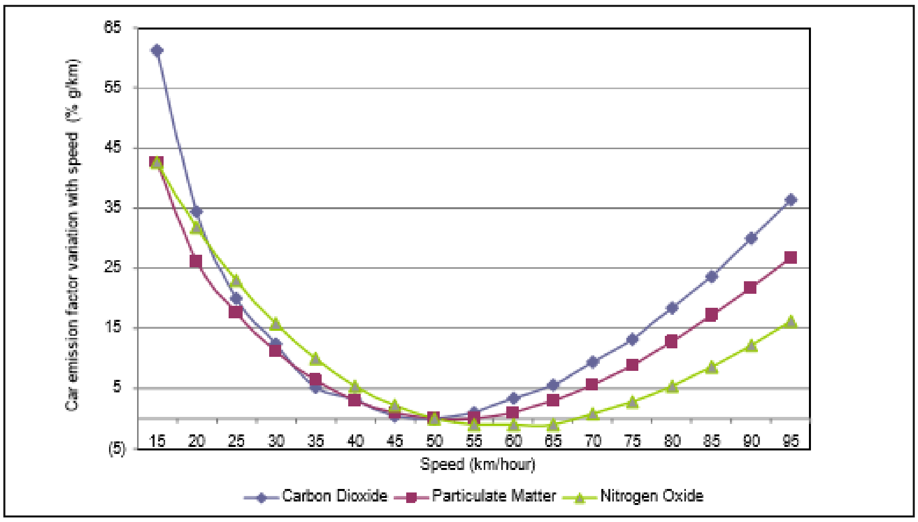

Figure 24: Impact of Speed on Vehicle emission (Source: Singru (2010))[48]

But depending on different types of vehicles, there are different achievements and improvements in GHG emission. Although, diesel fuel provision brings increased GHG emission and TTW based on more improved vehicle technologies, prediction is based on reducing the total GHG emission chain, from bus production, provision of fuel all along to driving.

5.6 Scenario for the GHG emissions of buses

For 2030 year, based on available data and using equations (6, 7), following GHG emission for each LCA step is presented in Table 21:

Table 21: GHG Emission of each LCA step for 2030

Fuel	CO_{2eq} (g/kWh)	$GHG_{CO2eqTTW}$ (kg/km)	GHG_{Manuf} (kg/Bus)[3]
Diesel	**51.29**	**0.89**	**2 547.2**
LNG	**25.38**	**0.93**	**3 034.6**
Hydrogen	**337.94**	**0**	**4 552**
Electricity	**279.68**	**0**	**2 812.1**

Better efficiency of conventional fuels and lower exhausted emission is the main aim of diesel fuel production in oil refinery. Starting from this point, annually long-term reduction factor by producing diesel and natural gas may be ascertained by 1%. Under the assumption that in the future, there will be predominately electricity and hydrogen from renewable energy, annually reduction for TTW could be considered using electricity and hydrogen fuels excludes tailpipe emissions. Upstream emissions rate is based on the GREET1_2015 estimate of hydrogen produced from steam-methane reforming of natural gas and represents our assumption of a long-term 1% reduction per year in GHG emissions rates due to improvements in hydrogen production process, while a long-term 2% reduction per year for electricity in the upstream grid[68].

GHG for Bus manufacturing is not changed until 2030. Under all these assumptions, the calculated $GHG_{CO2eqWTT}$ emission using equation (7) is presented in Table 22.

Table 22: GHG emission for WTT

Fuel	$GHG_{CO2eqWTT}$ (kg/km)
Diesel	**0.3**
LNG	**0.15**
Hydrogen	**1.05**
Electricity	**0.45**

Using equation 6 GHG for WTW cycle could be calculated and the results are as shown in Table 23.

Table 23: GHG WTW Emission for 2030

Fuel	Diesel	LNG	Hydrogen	Electricity
GHG_{WTW} (kg/km)	**1.19**	**1.08**	**1.05**	**0.45**

In the past decades, traffic in the EU has continuously increased and the big challenge is to reduce GHG emission. Considering large scale energy production, industry and buildings sectors, clear, absolute energy savings and CO_2 reductions could be achieved, despite growth. Comparison of four inspected types of vehicle for the year 2030 is graphically presented; and visually, it is easy to recognize that GHG total emission is convincingly the lowest for battery vehicle and unfavorable for diesel buses. For the other three types, the expectation is similar, however slowly lower emission by fuel-cell buses.

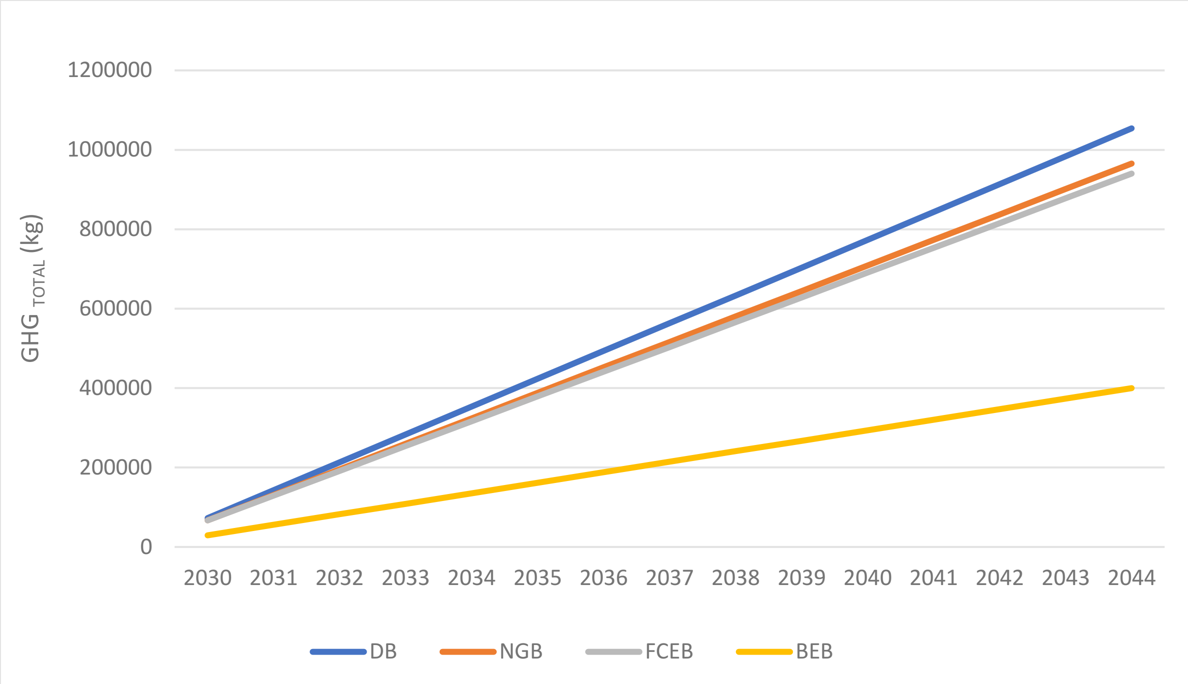

Figure 25: Accumulated GHG emission from 2030

In recent decades, worldwide consumption of conventional road-based transportation fuels (gasoline and diesel) has increased by around 1.5% per year[49]. The source of electricity is a key to directly determining the net CO_2 emissions generated from battery-electric and fuel-cell-electric buses. For pure regenerative energy sources for electricity, the GHG reduction would be greater. Here, it is considered as mixed electricity sources.

6 Air pollution

As already mentioned, buses powered by fossil fuels are major contributors to air pollution. In fact, transportation emits more than half of nitrogen oxides in our air and is a major source of global warming emissions in the world[40]. While this air pollution carries significant risks for human health and the environment, through clean vehicles and fuels, we can significantly reduce emissions from the transport sector.

Greenhouse gas is marked as "the leading pollutant" and "the worst climate pollutant". Buses produce air pollution throughout their life cycle, including pollution emitted during vehicle operation and fuel production. Additional emissions are associated with refining and distribution of fuels and with manufacturing and disposal of the vehicle.

Air pollution from buses is split into primary and secondary pollutions. Primary pollution is emitted directly into the atmosphere; secondary pollution results from chemical reactions between pollutants in the atmosphere. Besides GHG emission, the following are the major pollutants from motor vehicles, which were examined in this study:

- Particle matter articles (PM), atmospheric particulate matter or fine particles, are tiny particles of solid or liquid suspended in a gas. PM, which is a product of incomplete combustion and a complex mixture of both primary and secondary pollutants. Primary PM is the fraction of PM that is emitted directly into the atmosphere, whereas 'secondary' PM forms in the atmosphere following the release of precursor gases (mainly sulfur dioxide (SO_2), nitrogen oxides (NO_X), ammonia (NH_3) and some VOCs)[69]. In terms of its potential to defect human health, PM is one of the most important pollutants, as it penetrates sensitive regions of the respiratory system and can cause or aggravate cardiovascular and lung diseases and cancers. In contrast, aerosol refers to combined particles and gas. Some aerosol particulates occur naturally, originating from volcanoes, dust storms, forest and grassland fires, living vegetation, and sea spray. Human activities, such as the burning of fossil fuels in vehicles, power plants and various industrial processes caused a contribution of aerosol particulates.

- Nitrogen oxides (NO_X) comprise a mixture of nitric oxide (NO) and nitrogen dioxide (NO_2). It is particularly nitrogen dioxide, which are expelled from high temperature combustion, produced during thunderstorms by electric discharge. Nitrogen dioxide is a chemical compound with the formula NO_2. It is one of several nitrogen oxides. NO_X constitute's a group of different chemicals that are all formed by the reaction of nitrogen — the most abundant gas in air — with oxygen. NO_X comprises colorless nitric oxide (NO) and reddish-brown, very toxic and reactive nitrogen dioxide (NO_2). NO_X emissions also lead to the subsequent formation of 'secondary' PM and ground-level ozone in the atmosphere and cause harm to the environment by contributing to the acidification and eutrophication of waters and soils[69]. One of the most prominent air pollutants, this reddish-brown toxic gas has a characteristic sharp, biting odor.

Vehicle emissions could be categorized into three types (exhausted, abrasion and evaporate emission). Exhausted emissions are emissions produced primarily from the combustion of different petroleum products such as diesel, petrol and natural gas. In this work, CO_2 emission from exhaust pipes of diesel and natural gas transport vehicles is analyzed. Abrasion emission is emission from mechanical abrasion and corrosion of vehicle parts. Abrasion is typical by PM emission and emissions from some heavy metals. Evaporation emission is the results of vapors escaping from the vehicle's fuel system. It is important for VOCs but in this work, it is out of scope[69].

The general development strategy for zero emission vehicles starts with conventional vehicles that are currently on the road. As is depicted in Figure 26, internal combustion buses produce high emissions due to fuel consumption. Hybrid electric buses have both an electric motor and an internal combustion engine, utilizing both electricity and diesel. While the bus can use diesel for the parts of its mileage, it can also run emission-free once switching to electric mode. Hybrid buses could be classified inot conventual hybrids and plug-in hybrids. Conventual hybrid buses recharge their electric battery from the energy gotten from brake system. It combines both diesel and electricity and reduce the fuel costs, and emission from fuel is reduced as well. The plug-in hybrid bus can be charged by being plugged into an outlet. This capability to be recharged reduced the need and consumption of diesel which directly has impact on more reduced emission from conventual hybrid electric bus. The all-electric mode of plug-in hybrids results in effectively zero tailpipe emissions in urban conditions. Battery-electric buses have an electric motor instead of a fuel tank and an engine. They are more efficient than hybrid buses. Fuel-cell-electric buses contain a fuel-cell system powered by hydrogen that generates electricity to operate the bus. The electricity used to power the bus, along with heat and water vapor, are the only byproducts of fuel-cells. Electricity is stored in battery system. These buses produced on average less emission than battery-electric buses. For lower emission, primary energy resources for electricity should be renewable resources. Because of that, zero emission vehicles are battery-electric and fuel-cell-electric vehicles.

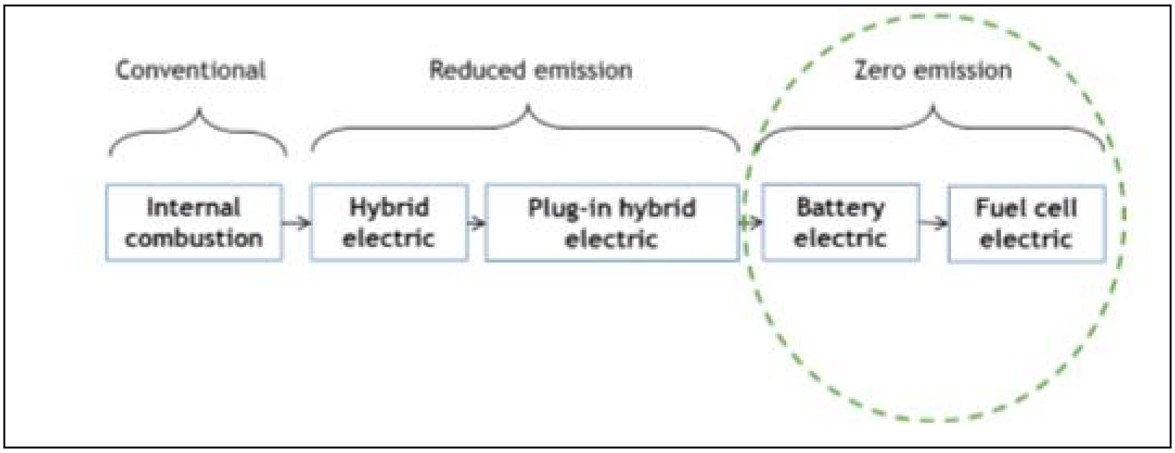

Figure 26: Development strategy for zero tailpipe emission vehicles (Source: Boer et al. (2013)) [51]

This chapter will introduce the impact on air quality (analyzed by NO_X and PM) from bus manufacturing step and fuel production and distribution.

6.1 NO_X and PM pollution of buses: State of the art

From 1990 to 2017, the whole transportation sector significantly decreased air pollution of the following air pollutants: carbon monoxide and non-methane volatile organic compounds NMVOCs (both by around 87 %), sulfur oxides (66 %) and nitrogen oxides (40 %). Since 2000, a reduction in particulate matter emissions (44 % for PM with a diameter of 2.5 µm and 35 % for PM with a diameter of 10 µm) has occurred[52]. Air pollutions from all transportation modes have declined since 1990, despite the general increase in activity within the sector across the EEA-33 (the 28 EU Member States plus Iceland, Lichtenstein, Norway, Switzerland and Turkey). Although CO, SO_X and NMVOC are not in the scope of this thesis, an overview of the main air pollution contributors in the EU by transport mode is presented in Figure 27.

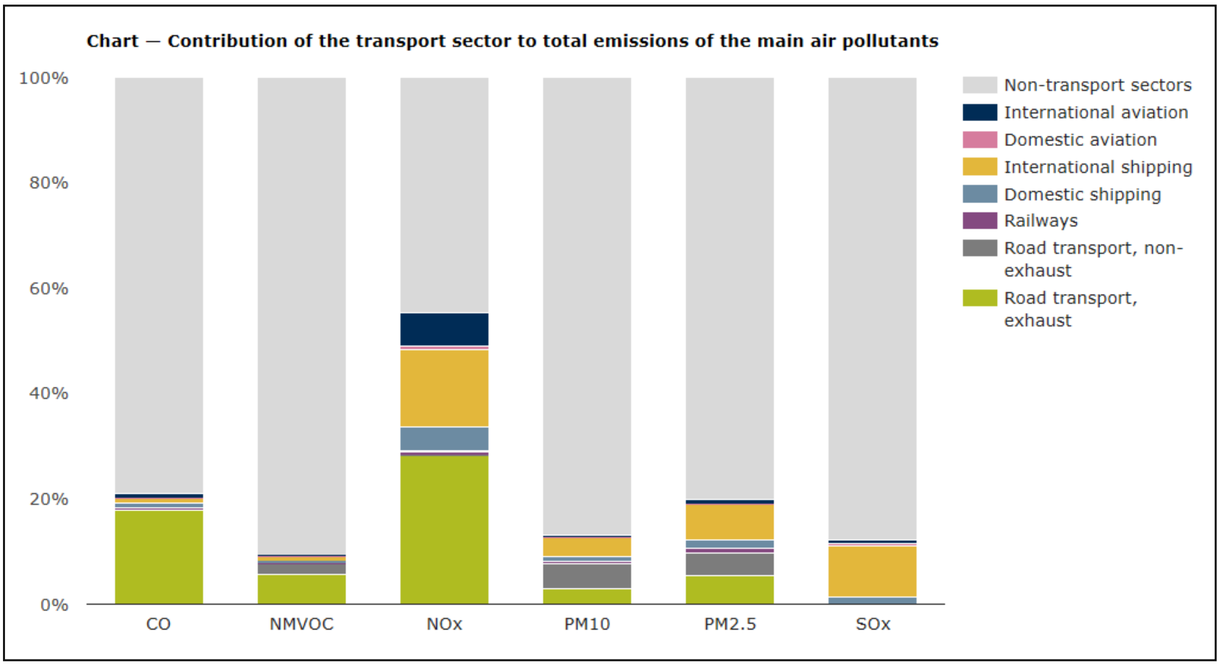

Figure 27: Contribution of the transportation sector to total emissions of the main air pollutants (Source: European Environmental Agency (2019)) [52]

Transportation is responsible for more than two-thirds of all NO_X emissions and accounts for a significant proportion (around 10% or more) of the total emissions of other pollutants. Road transportation accounts for a significant proportion of emissions of all the main air pollutants. Particularly from diesel passenger cars and buses is NO_X produced, and the focus for reduction should be on these segments. While emissions from road transportation are mostly exhaust emissions arising from fuel combustion, non-exhaust releases contribute to both NMVOC (from fuel evaporation) and primary PM (from tire and brake-wear, and road abrasion) emissions. Emissions of primary PM from road transportation have increased by 22% since 2000 and the relative importance of non-exhaust emissions has increased as a result of the introduction of particulate abatement technologies in vehicles, which has reduced exhaust emissions. In 2017, the non-exhaust emissions of PM (both $PM_{2,5}$ and PM_{10}) accounted for 55% of emissions from the road transportation sector compared with 27 % in 2000[52].

From a case study from North-Westphalia,[53] bus transportation has not so strong influence on air pollution and the major contributors are passenger cars (with diesel motor). Air pollution reduction in bus transportation alone will not significantly improve air quality and protect the environment. It is more productive to have a focus on another type of transportations, however, this study considered only bus transport.

Share of NO_X pollution in Germany regarding pollution source (cars, motorbikes, buses, light-duty vehicles, etc.) is depicted in Figure 28.

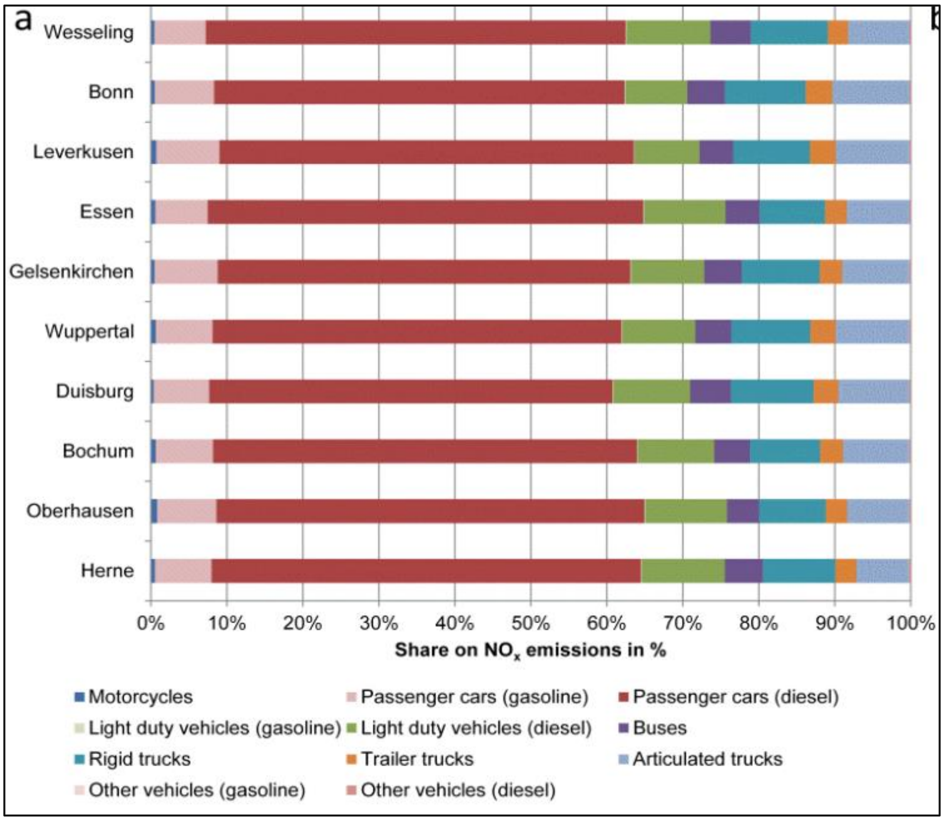

Figure 28: NO_X emissions of the 10 urban areas with the highest NO_X emissions in 2018 (Source: Breuer et al. (2020)) [53]

The distance-to-target chart indicates how current NO_X emissions compare to a linear emission reduction 'target-path' between emission levels from 2011 and Gothenburg emission ceilings from

2020 for each country. Negative percentage values indicate that the current emissions in a country are below the linear target path; positive values show that current emissions are above a linear target path to 2020[70].

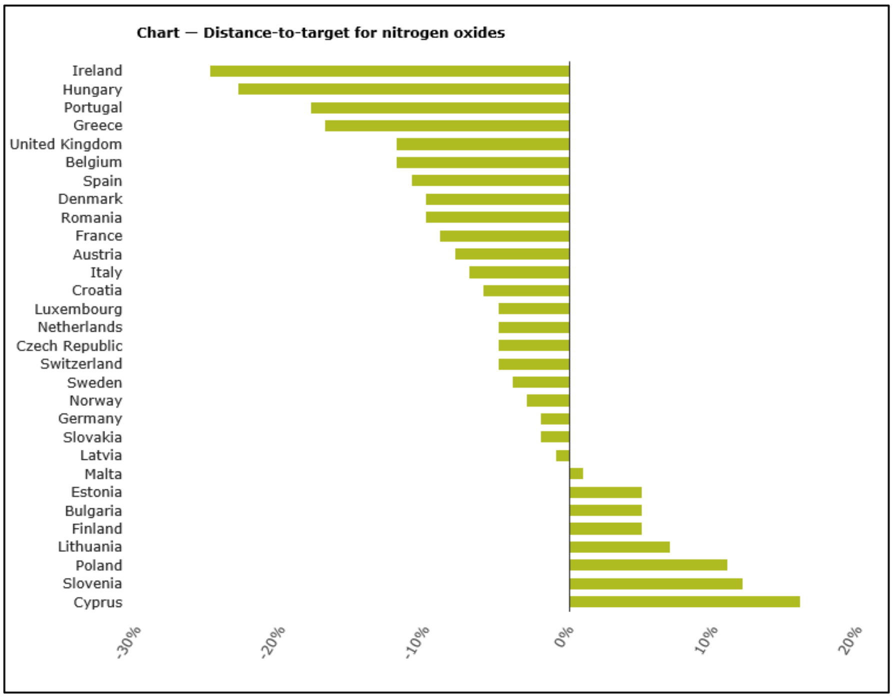

Figure 29: Distant to target for NOx (Source: European Environmental Agency (2020))[70]

Between 2005 and 2020 the EU members countries had to reduce NO_X emission by 42% by Gothenburg emission targets. For comparison, in entire EU in 2020 this expectation is full achieved and the result in emission of NO_X is reduced to 50%.

The main sector contributing to emission of air pollutants in Europe are transportation (split into road transportation and non-road which includes i.e. air, rail, sea and inland water transportation); commercial, institutional and households; energy production and distribution; industry (split into energy use in industry and industrial processes and product use); agriculture; waste (includes landfill, waste incineration with heat recovery and open burning of waste)[75].

The NOx emission share in the EU is illustrated in Figure 30. The newer Member States of the European Union have, in a number of cases, also undergone significant economical structural changes since the early 1990s, which has led to a general decline in certain activities that previously contributed to high levels of NO_X emissions e.g. heavy industry and the closure of older, less efficient, power plants, and replacement of old vehicles with newer vehicles that meet Euro standards. For both road and non-road transportation sectors, emissions of NO_X pollution have decreased significantly since 2000, although transported passenger and freight volume has increased.

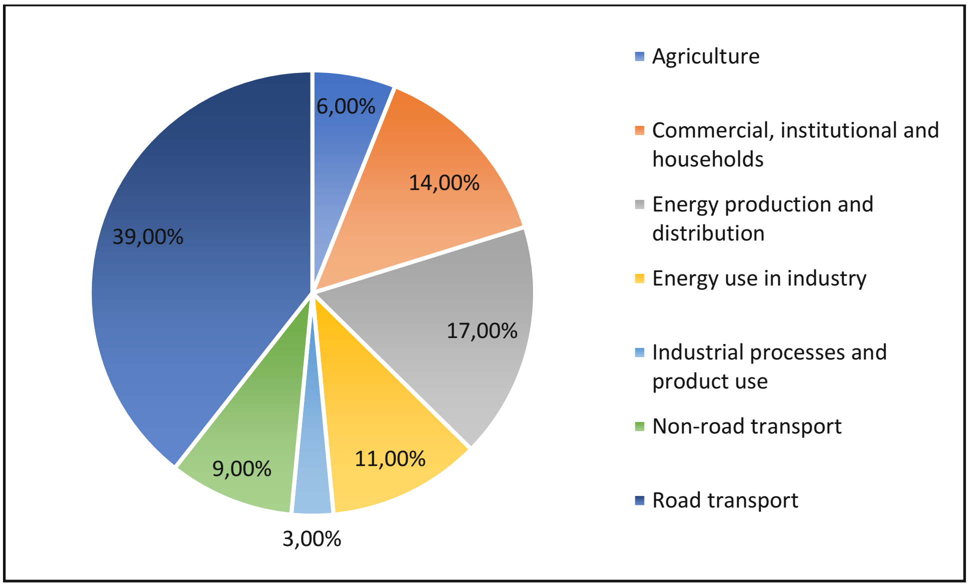

Figure 30: Sector share of NOx in the EU (Source: European Environment Agency (2018))[75]

NOx emissions and the sector contributions will change drastically in the future as a consequence of recent EU legislation. The decline of 50% of NOx emission is happening gradually because of the staged introduction of more stringent emission controls to new vehicles and plant and also the use of Euro 6 diesel engine, slowly transition on alternative buses.

The following picture describes PM pollution in different parts of Germany and the main sources for PM pollution by transportation.

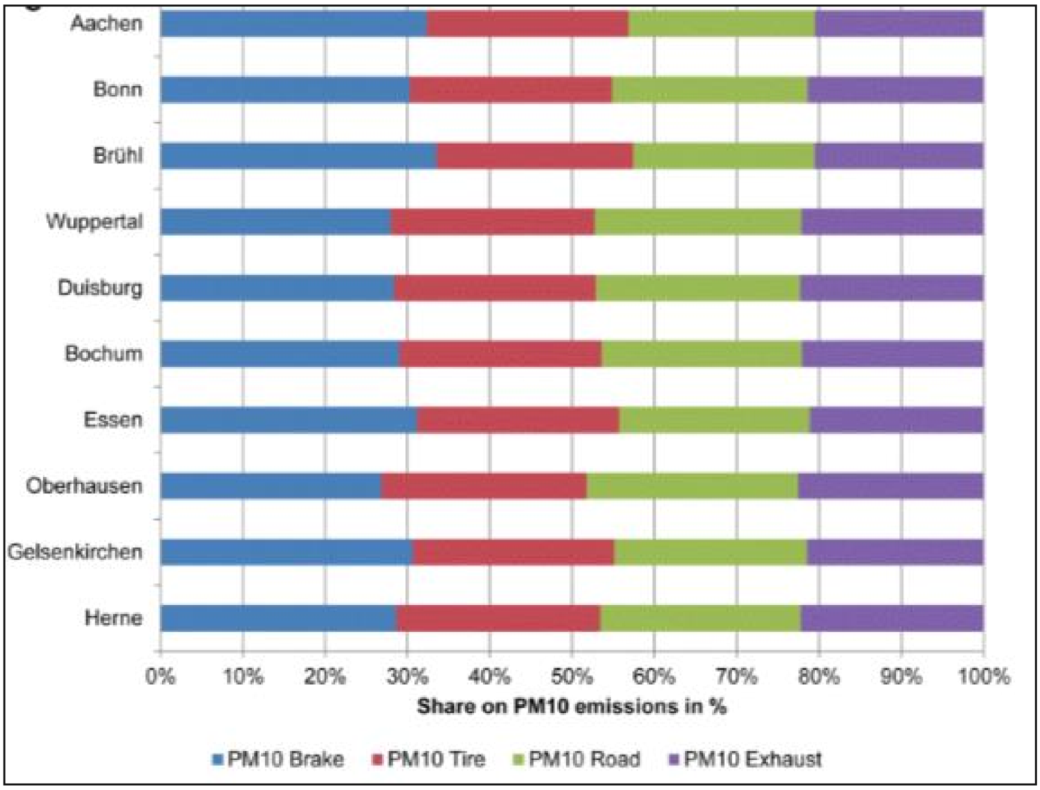

Figure 31: Percentage of total PM_{10} emissions by cause in urban area in 2018 (Breuer et al. (2020)) [53]

Figure 31 shows the percentage of calculated brake wear, tire wear, road surface wear and exhaust emissions of total PM_{10} emissions for the ten urban areas with the highest specific PM_{10} emissions in 2018. The shares of each PM_{10} emission source are mostly constant. On average, exhaust emissions make up about 21% of the total PM_{10} emissions. Furthermore, brake wear, tire wear and road surface wear are, respectively, responsible for 30%, 25% and 24% of the total PM_{10} emissions. These analyses were conducted in Germany. Under the assumption that in the EU are present similar road traffic condition, this share of NO_X could be applied to other countries.

Primary PM is commonly classified as PM_{10} and $PM_{2.5}$ and is mainly derived from fuel combustion for domestic heating, power generation etc[71]. The greatest share of PM_{10} in the EU takes Commercial, Institutional and Household sector and around 10% of the total PM_{10} emission in the EU is produced by road transportation. Reduced % of PM emission has taken place in the energy production and distribution sector due to factors including the fuel-switching from coal to natural gas for electricity generation and improvements in the performance of pollution abatement equipment installed at industrial facilities. Figure 32 presents sector share in EU of PM_{10} in 2018.

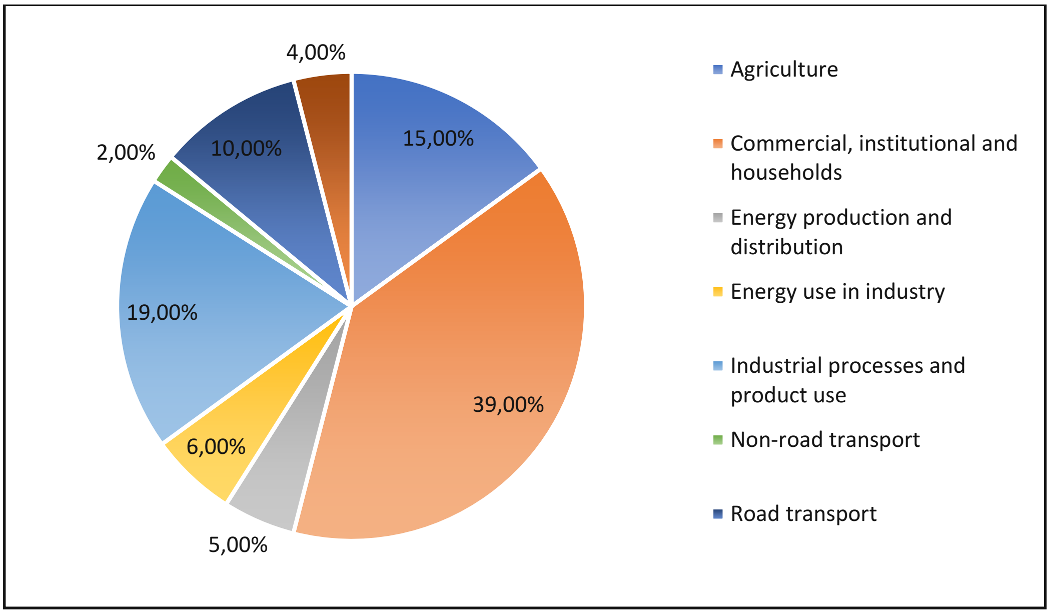

Figure 32: Sector share of PM_{10} in EU (Source: European Environment Agency (2018))[75]

Share $PM_{2.5}$ (particles with diameter of 2.5 micrometers or less) in the EU is in Figure 33. The road transportation share is 11%.

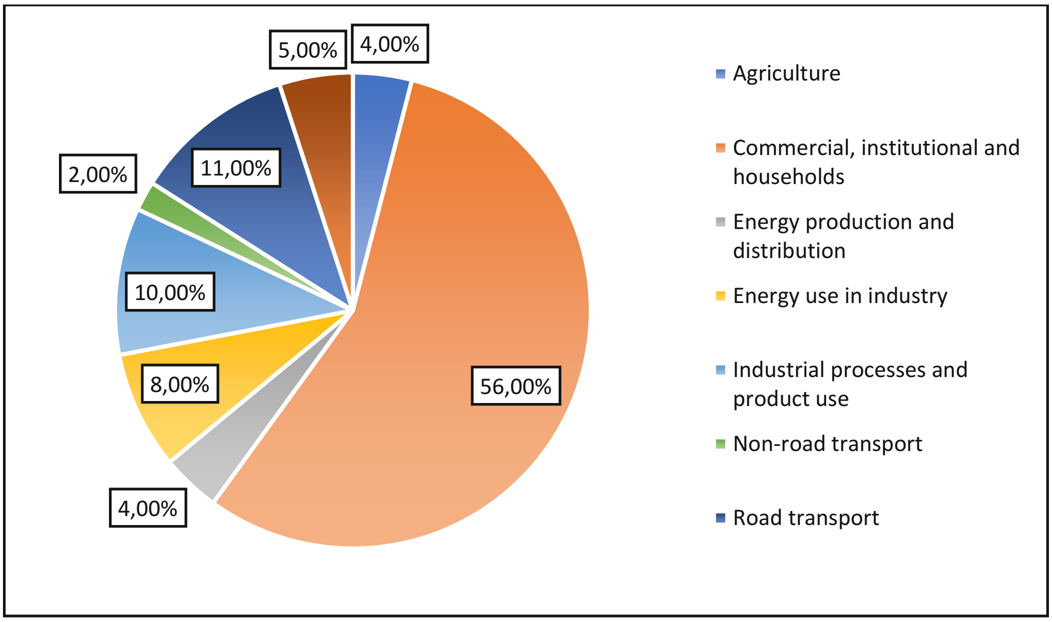

Figure 33: Sector share of $PM_{2.5}$ *in EU (Source: European Environment Agency (2018))*[75]

Current legislation that is often directed towards other pollutants will also have an impact on $PM_{2.5}$ emissions. $PM_{2.5}$ emissions are expected to decrease by 40% between 2005 and 2030 with a 30% cut in 2020. Stricter standards for diesel vehicles will contribute most to the decline, while no major changes in the emissions from biomass combustion are expected. Non-combustion emission (such as: road abrasion, brake and tyre wear…) are likely to increase.

6.2 Current NO_X and PM emission of buses

Because the transport grew more than was expected and partly because of NOx and PM pollutants, growth in diesel buses has been greater than expected, there are need for the analysis of current NOx and PM pollution. This chapter contains current NOx and PM pollution from WTT and TTW and graphically presentation of the accumulated pollution starting from the referent year 2018.

For year 2018, WTT air pollutions are shown in Table 24. Obviously, the most negative impact on air quality has electricity.

Table 24: *WTT NO_X and PM emission for 2018*[4, 54]

	NO_X (g/kWh)	PM (g/kWh)
Diesel (DB)	**0.141**	**0.006**
Natural Gas (LNGB)	**0.162**	**0.003**
Hydrogen (FCEB)	**0.326**	**0.028**
Electricity (BEB)	**0.60**	**0.14**

For Hydrogen production in 2018, the majority of hydrogen (~80%) was produced from fossil fuels by steam reforming of natural gas, partial oxidation of methane, and coal gasification. Other 20% of hydrogen production included biomass gasification, no CO_2 emissions, methane pyrolysis and electrolysis of water. For scenario in the future, this can be done directly with any source

of electricity (such as solar power, wind, water) with ration already mention 50% from NGSR and 50% from renewable energy. Electricity used for charging battery-electric buses are used from grid with contribution of fuels to electricity generation:
30% from renewables; 25% from nuclear energy; 21% from coal and lignite; 20% from natural and derived gas; 2% from oil; 2% from other fuels[76].

TTW process is the opposite process. During the driving of FCEB and BEB, there are no air pollution. The worst case is by burning diesel fuel. ZEVs do not produce tailpipe emissions, thus reducing roadside emissions and improving local air quality. However, ZEVs are not zero-emission in a regional or global sense because electricity (or hydrogen) generation can produce upstream emissions.

Table 25 contains TTW emission for both pollutants for the year 2018.

Table 25: *TTW NO_X and PM emission for 2018*[4]

	NO_X (g/km)	PM (g/km)
DB	12.94	0.24
LNGB	0.66	0.02
FCEB	0	0
BEB	0	0

The same approach as in previous chapter, is used to calculate air pollution according to equation (4) with all known parameters: WTT, TTW and bus-manufacturing generated emissions. The results are illustrated in Table 26.

Table 26: *NO_X and PM emission for 2018*[3]

	DB	LNGB	FCEB	BEB
Bus Manufacturing NO_X kg/Bus[3]	4.12	4.89	7.13	4.74
Bus Manufacturing PM kg/Bus[3]	1.21	1.32	2.68	2.12
NO_X WTW g/km	13.58	1.62	1.01	0.97
PM WTW g/km	0.27	0.02	0.09	0.23

It is assumed that in the present scenario, equal effort is being made to reduce NO_X and PM air pollution by all types of vehicles. Under all already described assumption about bus operation and suggested discount factor of air pollution through the years, accumulative NO_X and PM are illustrated in Figures 34 and 35.

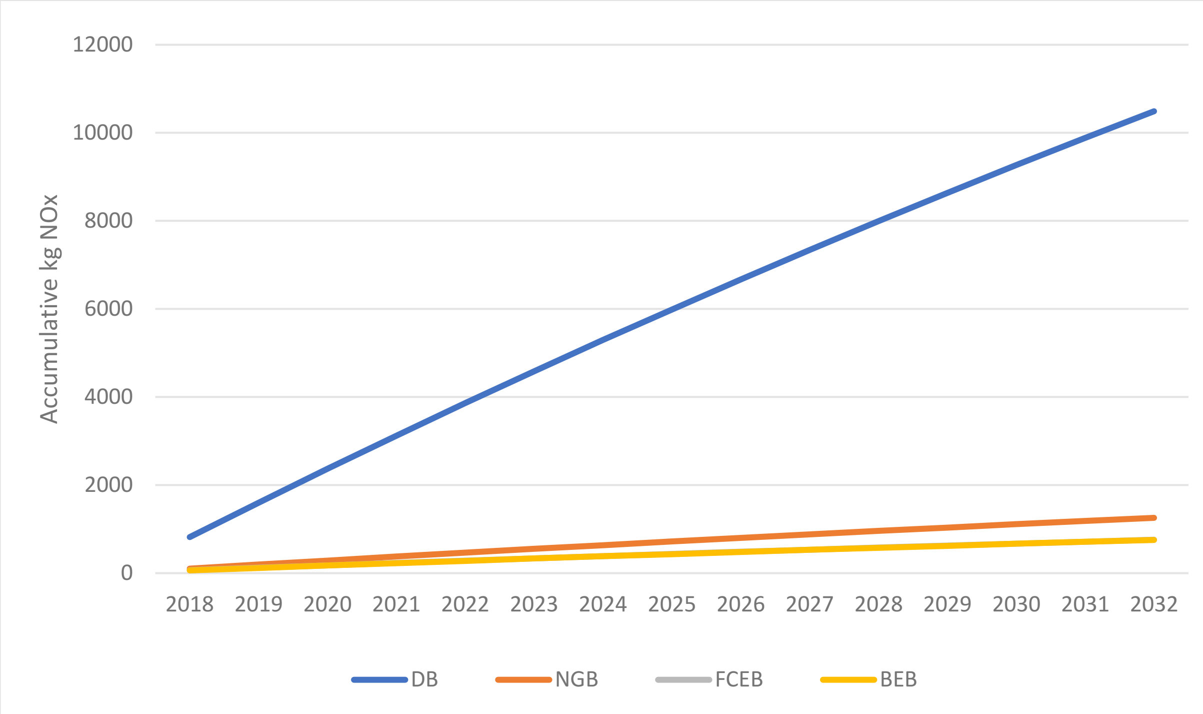

Figure 34: Accumulated NO_X air pollution from year 2018

It could be clearly concluded that NO_X pollution is the highest during the use of diesel fuel. Fuel-cell-electric and battery-electric buses results are almost the same and the curve could not be visible distinguished in Figure 34. Natural gas bus contributes remarkable lower NO_X pollution then conventional diesel one.

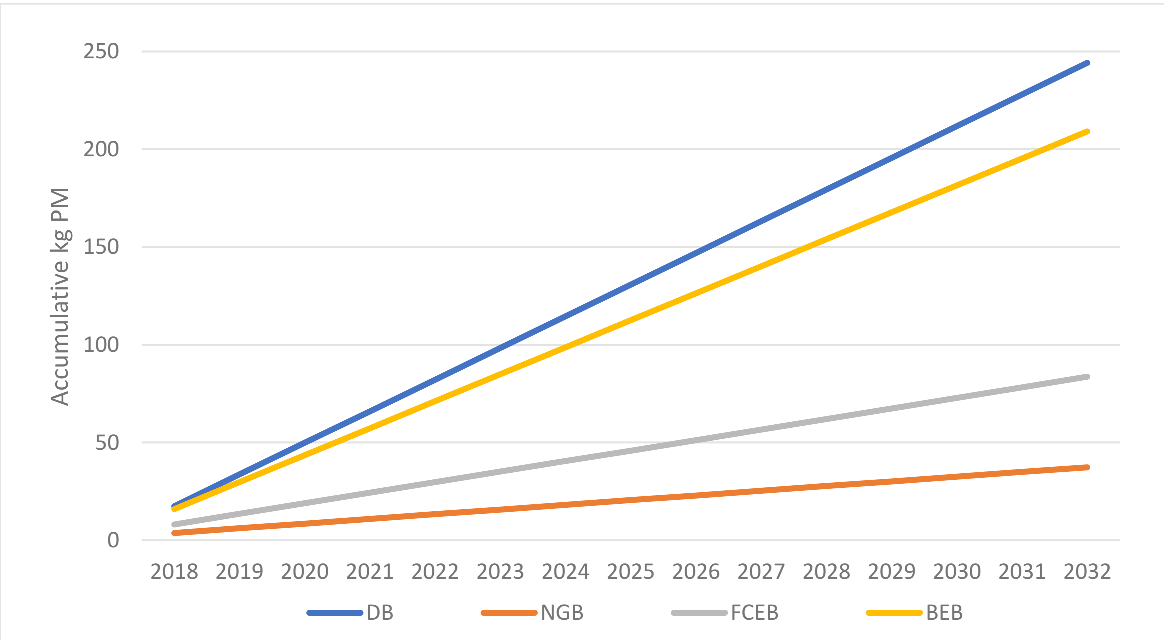

Figure 35: Accumulated PM air pollution from year 2018

Accumulative PM air pollution through the years of bus operation is immense for battery-electric and almost three times is PM pollution contributed then for fuel-cell-electric buses. Natural gas bus and fuel-cell-electric have the best performance, while diesel bus generates the highest level of PM pollution of all the analysed bus types.

6.3 Scenarios for NO_X and PM emissions of buses

More than 400 000 people dies prematurely in the EU due to air pollution per year, data from the year 2019, NO_2 toxic gases causes around 79 000 premature deaths. The European Environmental Agency estimates that road transportation contributes to excessive concentrations about 70% for NO_2 and about 30% for PM[40]. That makes air pollution the main environmental cause for shortened lives in the EU. The resulting health problems cost society an estimated 330-940 billion Euro per year. Over 90% of the urban population in the EU is exposed to concentrations of higher than the limit values recommended by the World Health Organisation (WHO). Among the most important pollutants are black carbon (BC), which is a part of particulate matter (PM), Nitrogen Oxides (NO_X) and ozone (O_3)[55]. This makes a valid reason for reducing air pollution in the future and this chapter will analyze the following scenarios.

The long-term objective of the European Union on NO_X and PM emissions is an overall reduction of 95% by the year 2030, from 2016[56].

Estimated WTT NO_X air pollution by fuels is shown in the Table 27.

Table 27: WTT NO_X and PM emission for 2030[4]

	NO_X (g/kWh)	PM (g/kWh)
DB	**0.14**	**0.008**
LNGB	**0.16**	**0.004**
FCEB	**0.18**	**0.012**
BEB	**0.44**	**0.083**

Under the assumption that certain effort (such as: develop stringent Euro 7/VII emissions standards for bus vehicles to achieve further reductions of air pollutant emissions in line with WHO guidelines. For example: reduce and align diesel and natural gas bus emission limits, increase emission durability requirements and increase the amount of regulated pollutants) will be invested in decreasing air pollution in exhausted gases, it could be supposed that 2%[58] annually is improving factor and beginning with referent values from the year 2018. Calculated data for TTW are illustrated in Table 28.

Table 28: *TTW NO_X and PM emission for 2030*

	NO_X (g/km)	PM (g/km)
DB	**10.22**	**0.19**
LNGB	**0.52**	**0.01**
FCEB	**0**	**0**
BEB	**0**	**0**

Bus manufacturing air pollution in 2030 captures the same values as in 2018. Bus disposal in these meaning is neglected here. The results of Equation 6 used for WTW calculation for the year 2030 is shown in Table 29.

Table 29: WTW NO_X and PM pollution for 2030

	NO_X (g/km)	PM (g/km)
DB	10.85	0.23
LNGB	1.47	0.03
FCEB	0.56	0.04
BEB	0.71	0.13

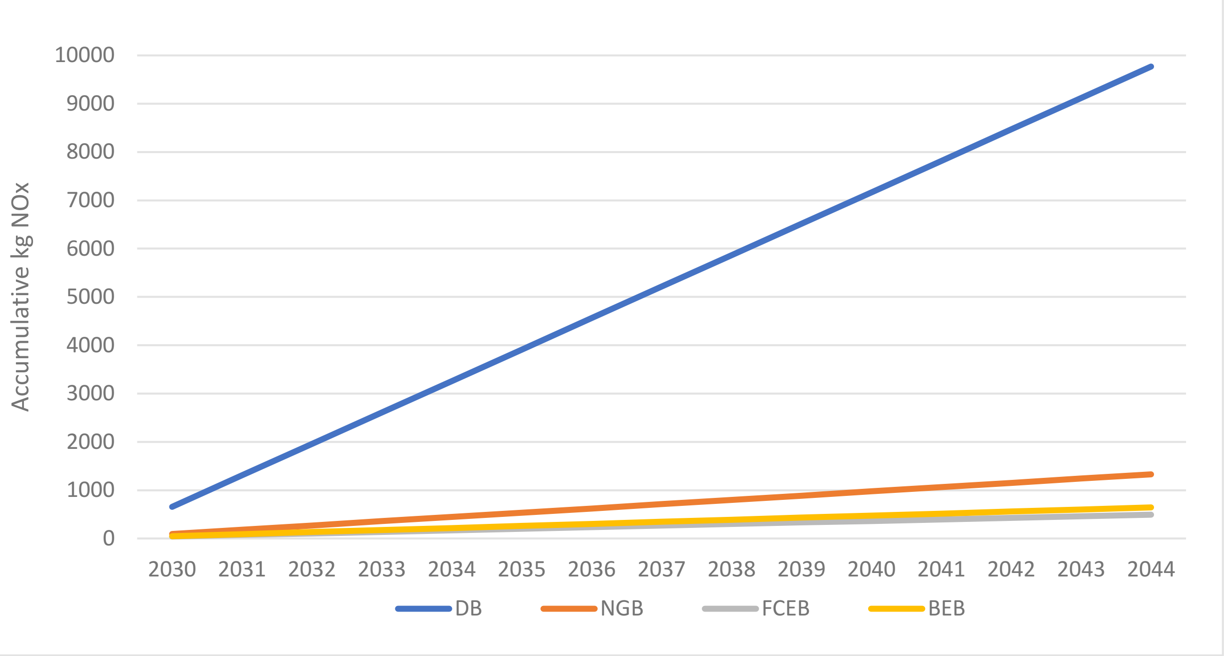

Figure 36: Accumulated NO_X air pollution from year 2030

Estimated air pollution indicates for the lowest emission using fuel-cell-electric and battery-electric bus. The worst influence on air quality will caused using diesel machines. NO_X pollution by diesel bus will be 20 times higher than by alternative bus in the 2030. It could be a solid reason to invest more in the future in diesel drivetrain technology to reduce air pollution by using itself.

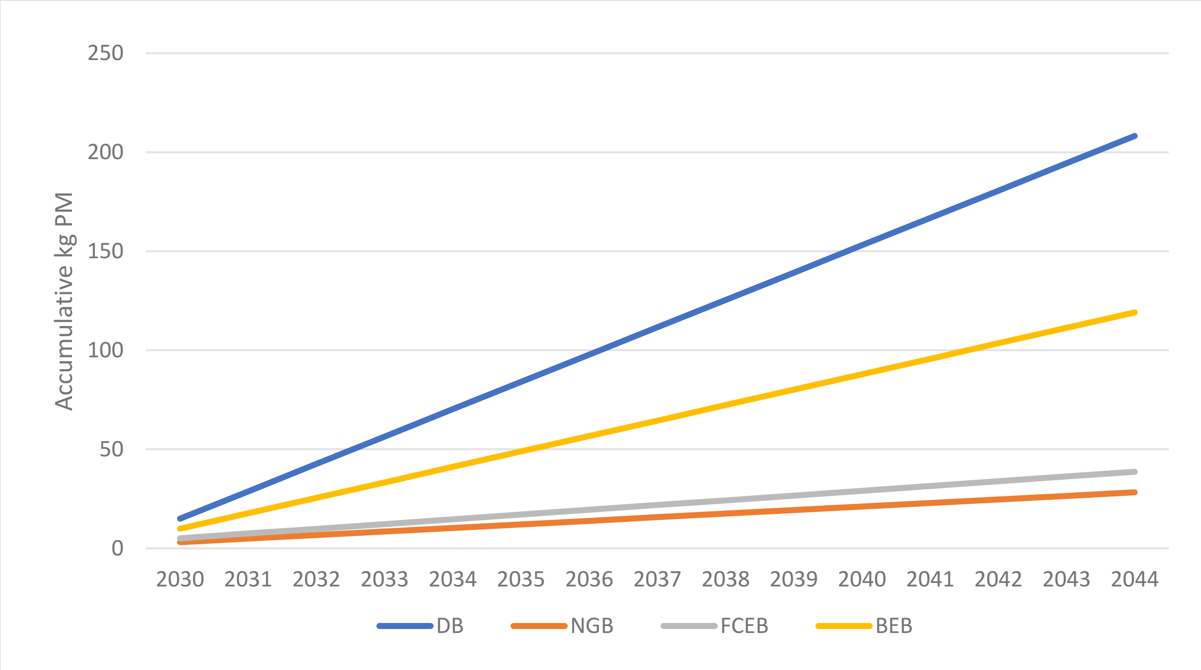

Figure 37: Accumulated PM air pollution from year 2030

Expected and estimated PM emission constellation in the future will look different from the present day records. Diesel engine PM emission does not largely reduce pollution, as predicted, it will be the most important contributor of PM emission in the 2030 year. Natural gas will hold the position as the least PM polluter. The focus on the future should be on PM reduction for diesel and battery-electric bus. Operating fuel-cell-electric bus produces similar PM pollution as natural gas.

The emission modeling presented in this paper indicates that extensive, near-term transitions to cleaner engine technologies that is non-fossil fuels will be needed to comply with the emissions reduction and environmental protection goals. We estimated that all new buses purchased beginning the year 2020 and continuing thereafter will need to meet Euro VI or better emissions performance in order to achieve enough PM and NO_X emissions reductions. There is a predicted usage of ZEV in bus transport or new buses with Euro VI engine[50]. Figure 38 presents a timeline with pre-sumable bus scenarios in the EU.

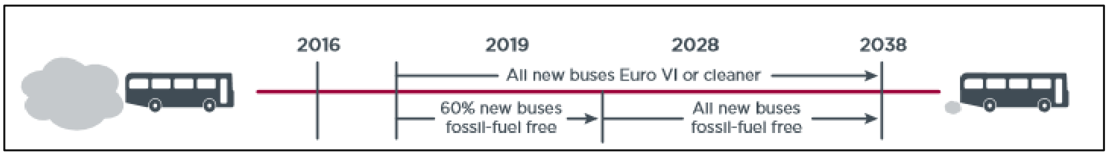

Figure 38: Emissions reductions estimated for transit bus fleet (Source: Bergk et al. (2017))[47]

Euro VI engines are effective at controlling emissions of black carbon (BC), an important short-lived climate pollutant. Up to 75% of diesel particulate matter emitted from older technology diesel engines contains BC. However, Euro VI engines reduce diesel BC emissions by 99%, primarily through the application of a diesel particulate filter[57].

A reduction of NO_X emissions by more than 10 times[54] can be observed for Euro VI buses, with the use of selective catalytic reduction (SCR) systems using aqueous urea solutions for Euro VI bus's exhaust emissions control. The year 2050 air pollution projection for DB emission shows that DB emission will be 10 times less than WTW air pollution for NO_X and PM when compared to the year 2018. Traffic management in industrial countries has been estimated to reduce emissions by 2–5% overall, but by much greater proportions in specific corridors or areas [58].

The reduction of air pollution from the bus transportation sector depends on adjusting the structure of bus transportation networks and prioritizing it to transportation methods with fewer pollutant emissions. The vehicle composition for each mode of transportation must be adjusted to reduce total fuel consumption and pollutant emissions. This analysis was aimed to better understand the current status of air pollution emissions from the transportation sector and the emission contributions of different modes of bus transportation in the EU. There are differences in the amount of produced air pollutants when the used methodology is applied to all four different types of buses quantified. Based on the obtained results, suggestions are proposed to reduce air pollution in the bus transportation sector. The natural gas bus provides the lowest level of produced PM and some but insignificant amount of NO_X. The best solution regarding air pollutants is definitely fuel-cell electric bus which produces the lowest emission of NO_X and PM in all four analyzed bus types. As expected, diesel bus is the most undesired case in air pollution analysis in the future and from this, there is one more recommendation for transition from conventional to alternatively fueled buses.

7 Legal and regulatory aspects

One of the questions of this study are the proper policies for the promotion of alternative solutions.

Legal regulatory, policies, directives and frameworks in sustainable transportation are very important. Without developed regulations and targets, we are not able to save and protect the environment and life in the whole world as well as smartly use the limited available resources. The main task of global and local policies is to stop the dependence on fossil fuels in transportation sector. For vehicles driven by alternative fuels, such as electricity, hydrogen and hybrid, the policies are divided in two segments: promotion and facilitating deployment of new growing technologies; and evaluation and presentation of power generation in comparison to conventional fuels which are covered with these two points, with special focus on network infrastructures and working on the standardization issues.

Reducing the unfavorable effects of the transportation sector is an important EU policy goal. The main required steps are switching transportation to the least polluting and most efficient modes, using more sustainable road transportation technology, fuels and appropriate infrastructure, ensuring that transportation prices absolute reflect negative environment and health influence. The EU strategy has focused on decarbonizing transportation. The EU Commissions 2018 strategy “A clean Planet for all: A European strategic long-term vision for a prosperous modern, competitive and climate neutral economy” searches for a way of transition towards “net-zero” GHG emissions in the whole of EU by 2050. Transportation is the most relevant system-based approach, underlines the importance of switching to low-carbon modes and zero-emission vehicles, underlines the central function of electrification and renewable energy sources and pushes for operational efficiency improvements. It projects for urban planning and the realization of the full benefits of public transportation. “The European strategy for low emission mobility” from 2016 has revealed a more efficient transportation system, the utilization of low-emission fuels and transition to low- and zero-emission vehicles in road transportation[72].

The EU regulation and legislation directly marked environmental and health influences of road transportation by setting binding rules. These rules include emission limits for cars, vans, trucks and buses, specific requirements for transportation fuels and noise maps and noise management plan for major transportation infrastructure, as airports and main bus stations.

Only the most important regulations will be mentioned and discussed here. There are several significant points regarding emissions limitations and fuel utilization:

- Directive on the promotion of clean and energy-efficient road transportation vehicles (2009/33/EC) - Revised Clean Vehicles Directive (2019/1161) [61]
- Regulation (EU) 2019/1242 of the European Parliament and of the Council setting CO_2 emission performance standards for new heavy-duty vehicles [61]
- Directive 2009/30/EC of the European Parliament and of the Council [61]

Public transportation is a key element of sustainable mobility in cities, and its quality should be maintained in order to keep existing users and attract new ones. Improving the attractiveness of public transportation itself include improving operational efficiency, coordinating tariffs and timetables, and enhancing accessibility and interchange facilities.

Promoting a large-scale deployment of clean, alternatively fueled buses in Europe is crucial for rapidly transition to low-emission buses. In order to increase the quality of life of citizens, reduce noise and improve air quality, the representatives of transportation authorities are responsible for applying transition to alternatively fuelled buses. Bus manufacturers and infrastructure providers should support this initiative by decreasing average prices of such buses. Bus manufacturers should continue extending the range of available vehicles, improve their reliability and decrease prices. Transportation authorities and grid network providers need to commit to establish corresponding efforts to plan and build a suitable infrastructure. Public procurement has the significant role in the declaration of the intent on promoting clean buses in Europe. Energy taxation schemes could make the right incentives for procurement, including policy changes to achieve a more equal tax treatment of clean alternatively fuelled buses. Financial institution should support the aims of this initiative in Europe through attractive and innovative financial mechanisms. The benefits from this change in bus transportation could be demonstrated through monitoring of noise and air pollution, with the one goal, to improve the quality of life in rural and urban area.

Under the EU State aid rules, the European Commission has approved increased capital to support public transportation with alternative buses in Germany. The total budget of 650 million euro is intended for the purchase of electric buses and the construction of related recharging infrastructure. The German aid scheme will apply from the year 2018 until the end of the year 2021 and is intended to cover the additional costs for the purchase of electricity operated or rechargeable hybrid buses instead of conventional buses with diesel engine and the realization of the charging infrastructure necessary to drive these buses. The European Commission had determined in 2018 that plan in Germany to support electric bus transportation countrywide were agreed with the EU state aid rules. The idea is also to ensure that buses from public transportation are powered by electricity from renewable energy sources. With this schema, GHG emission should be reduced for 45.000 tonnes of CO_2 equivalents per year, what is aligned with the EU's climate environmental target and European strategy for low-emission mobility. Air quality will also be improved and reduced air pollutant, especially around 170 tons per year of lower NO_X emission. The European Commission confirmed that the benefits from this project in terms of environmental improvement are impressive and the aid scheme was approved. A similar model could be applied in other EU countries with the same goal[74]. Some of the measure should be a ban on fossil fuel vehicle sales by a given year, but no later than 2035 for buses and trucks and comprehensive European electric and fuel-cell vehicle charging infrastructure development plan with short and medium-term targets, depending on the population and traffic density. There are also some recommendation to make easier transition on alternatively fuelled buses as systematic EU support to cities and municipalities in further developing bus public transportation systems, including financial support to provide affordable transportation fares.

Directive on the promotion of clean and energy-efficient road transportation vehicles (2009/33/EC) - Revised Clean Vehicles Directive (2019/1161) of 12.07.2019:

The Union is committed to a sustainable, competitive, secure and decarbonized energy system. The Energy Union and the Energy and Climate Policy Framework for the period between 2020 and 2030 establishes ambitious requirements for the Union to further reduce GHG emissions by at least 40% by 2030 as compared with 1990, to increase the proportion of renewable energy consumed by at least 27%, to make energy savings of at least 27%, and to improve the Union's energy security, competitiveness and sustainability. Emissions of air pollutants from transportation that are harmful to health need to be significantly reduced without delay. This can be achieved by an array of policy initiatives, including the use of public procurement of clean vehicles.

Innovation of new technologies helps to lower GHG emissions, supporting the decarbonisation of the transportation sector. An increased uptake of low- and zero-emission road vehicles is likely to reduce GHG emissions and certain pollutant emissions (PM, nitrogen oxides and non-methane hydrocarbons) and to promote competitiveness and growth of the European industry in the increasing global markets for low- and zero-emission vehicles. A strong support from key stakeholders for a definition of clean vehicles grounded on the requirements for the reduction of GHG emission and air pollutant emission from light-duty vehicles. To ensure adequate motivations to promote market uptake of low- and zero-emission vehicles in the European Union, provisions for their public procurement under this Directive should be aligned with the definition of zero- and low-emission vehicles provided for in Regulation (EU) 2019/631 of the European Parliament and of the Council Regulation (EU) 2019/1242 of the European Parliament as well as of the Council setting CO_2 emission performance standards for new heavy-duty vehicles of 20 June 2019.

The general objective of this Regulation is to accelerate the public procurement of clean (i.e. low- and zero-emission) vehicles in the Union and thus to support the modernization of the European mobility and transportation sector. This should support market for the promotion of these vehicles, particularly in the heavy-duty transportation sector. It should further improve the contribution from the transportation sector to the reduction of CO_2 and air pollutant emissions and contribute to competitiveness and growth. In addition, this initiative supports more effective public procurement policies at domestic level, which are better aligned in terms of strategic direction and market impact. It should reduce information cost for public and private actors and simplify the implementation process. Heavy-duty vehicles, including lorries, buses and coaches, produce around 6% of total GHG emissions in the EU and about 25% of total road transportation GHG emissions. Without further measures, the share of GHG emission from heavy-duty vehicles is expected to grow by 9% in the period from 2010 to 2030. Currently, the EU law does not describe any GHG emissions reduction requirements for heavy-duty vehicles, and therefore specific measures for such transportation are required to avoid GHG emission increasing.

In order to contribute to achieving the EU's target of reducing its greenhouse gas emissions by 30% below 2005 levels in 2030 in the sectors and to ensure the proper functioning of the internal market, the specific GHG emissions of the EU fleet of new heavy-duty vehicles shall be reduced compared to the reference GHG emissions for the reporting periods of the year 2025 onwards by 15%; as well as for the reporting periods of the year 2030 onwards by 30%. To provide and ensure uniform conditions for the implementation of this Regulation, implementation of the measures should be conferred on the Commission. Implementing powers in relation to identifying vehicles that are certified as vocational vehicles and applying corrections to the annual average specific GHG emissions of a manufacturer, reporting deviations in GHG emissions values, conditions under which the reference GHG emissions have been determined and if necessary, to correct it in order to ensure certain parameters relating to real GHG emissions and energy consumption of heavy-duty vehicles, verification that GHG emission and fuel consumption in the technical description for customer correspond to the GHG emission in operation; are the several of the relevant parameters for the implementation of this Regulation. Until 31 December 2022, the Commission will contribute a study to the European Parliament and to the Council on the effectiveness of this Regulation, on the GHG emissions reduction target and the efficiency of the mechanism for zero- and low-emission heavy-duty vehicles applicable from 2030, on setting GHG emissions reduction targets for other types of heavy-duty vehicles, including trailers, buses and coaches, and vocational vehicles, and on the introduction of irrevocable emissions reduction aims for heavy-duty vehicles for 2035 and 2040.

Directive 2009/30/EC of the European Parliament and of the Council, is related to fuel quality and monitoring of fossil fuels and controlling the reduction of GHG emissions. According to the Directive 2009/30/EC of the European Parliament and of the Council, until end of the 2020, GHG emissions should be reduced up to 10% per unit of energy from supplied fuel in comparison to produces GHG emission in 2010, or 30% in comparison to produces GHG emission in 1990. The GHG emission reduction should be involved by using alternative fuel and lower GHG emission during fuel production. Additional 2% should be realized by using electric and emission free vehicles. This directive doesn't support the destruction of biodiversity and the deterioration of arable land. High concentration of biofuels in the fossil diesel blends is possible and up to B10 blend standardization is one of the major tasks for biofuels technologies in this directive. Harmonization of the rules for fuels, setting technical specifications on health and environmental basis, reducing the sulphur content of diesel and petrol to 10 mg/kg max.

By 31st August each year, the Member States must submit a summary of fuel quality monitoring data collected during the period January to December, for the exact whole previous year, in accordance with Article 8(1) f Directive 98/70/EC as amended by Directive 2009/30/EC. EEA managed delivery process.

8 Conclusions

This thesis analyzed and evaluated significant economic and environmental parameters, such as bus costs, GHG emissions, NO_X and PM pollutants, in the bus transportation sector, as explained in Chapter 1.2.

Conventional diesel buses are predominantly utilized in the EU currently. Each year, there are more registered new alternative buses, e.g. 1 900 electrical and hybrid buses in 2018 and 3 800 in 2019. On the contrary, the number of registered diesel buses decreases yearly by about a hundred. Currently, the share of conventional buses versus alternative buses is 85% versus 15%. The Netherlands, France, Germany, Denmark, United Kingdom, Norway have the largest number of new electric buses registered (about 100-400 buses per country). Austria, Denmark, Finland, France, the Netherlands, Romania, Sweden and Norway have more than 5% share of electric buses in their own bus transportation. Estonia, Greece, Hungary, Ireland and Slovakia do not have developed infrastructure and network for electric buses and have opted for diesel buses. Based on available data, it was assumed that for a unified bus transportation in the EU, countries without electric buses should invest effort and capital to achieve a similar level of alternative bus transportation utilization[3]. There were more than 4 000 electric buses running in the EU in 2020.

Obtained results from TCO analysis remain the primary decision parameter for most public authorities in the selection of a bus type. Alternative fuel and bus technologies solutions have higher investment costs. However, these can indicate cost savings over the lifecycle due to lower fuel costs, CO_2 emission tax costs and maintenance costs. The economic parameters to be considered are purchase cost, fuel costs, CO_2 tax emission costs and maintenance costs with a focus on battery replacement costs. The scenarios used for the development of TCO with and without CO_2 increasing tax emission cost and with and without battery and fuel cell replacement in the future. In the long term, the most cost-effective outcome is the utilization of BEB. Including TCO scenario (2018 and on) with increasing CO_2 tax emission and replacement costs BEB has 4% lower TCO than DB. FCEB is not competitive with diesel bus (even 210% higher TCO). This methodology confirms that in the year 2030, the lower TCO costs for electric buses will be achieved. The purchase costs for electric buses will be reduced. Furthermore, for NGB and DB there will be no remarkable difference. The important objective is the development of new battery materials and battery design. To be more accessible for the bus transportation sector, the aim is to optimize charging time, costs and extended duration of driving range for battery. In the long term, TCO of DB will increase due to CO_2 taxes applied. BEB will have the lowest energy related costs (electricity costs and CO_2 tax emission costs) and purchase costs. Future technological development of BEB or FCEB which avoid obligatory replacement will meet acceptable quality to price ratio for end customers. Considering this scenario with CO_2 tax emission increasing and without replacement costs for battery and fuel cell, TCO for BEB will be 26% decreased and FCEB 12% decreased TCO compared to diesel bus.

Environmental assessment results showed that zero emission buses with BEB technology is the most efficient alternative for short ranges while FCEB technology is suitable for long ranges. Immediate use of alternative buses is desirable due to the reduction of GHG emissions and air pollution. If renewable energy is used for the electrolysis process of hydrogen production and electricity production, we could obtain almost zero emission bus according to TTW analysis. GHG scenario from 2018 indicates 33% lower generated GHG emission by BEB and 16% lower emission by FCEB when compared to DB emission. Predictions are even more in favor of alternative busses when looking much further into the future. Based on the GHG scenario from 2030, 60% lower GHG emission by BEB is expected than DB. The total GHG emission produced by BEB from 2030 and thereafter is 50% reduced when compared to 2018. BEB has the lowest GHG emissions contribution and from this point of view, it is the best bus alternative technology solution in order to significantly decrease the GHG emission to reach the EU goal. NO_X and PM are in this thesis analyzed as the relevant air pollutant from bus transportation. The NO_X emissions' reduction potential is 93% for BEB and FCEB in comparison with DB in all analyzed scenarios. The most likely value of around 50% higher NO_X emission generated by BEB than FCEB in the future scenario. According to the obtained results from PM calculations, the lowest level of PM pollutants is produced by NGB and FCEB, even 85%-87% lower than the conventional bus. BEB bus produces higher PM pollution amounts (just 45% lower than a conventional bus in the future), however, it is concluded that even slightly higher PM emission by BEB could compensate for low NO_X pollution if compared to other vehicle types. Despite the fact that BEB have zero tail-pipe emissions, they do not meet the PM emission standards when supplied with mix electricity from a power plant. BEB produces a lower noise level than DB. For a healthier life and cleaner environmental, a full transition to BEB and FCEB will be needed. They vibrate less, have no exhaust and have reduced noise.

To avoid dependence on oil and to increase environmental benefit, governments should support using alternative buses with subvention due to the high cost of ownership of BEB and FCEB. The EU Commission has created a few policies and legislative suggestions as to access the road market (the

EU has created a framework to encourage the Member States to use taxation and infrastructure taxation fairly to promote the 'user pays' and 'polluter pays' principles) and better social legislation for road transportation (all new city buses should be zero-emission vehicles or use biogas by 2025). The social acceptance of BEB and FCEB should better engage more of public opinion and include public engagement. Infrastructures must be developed, that will require important standardization efforts by the government. The promotion of BEB, as well as FCEB, is crucial through different ways of education. Consumers should be able to recognize the need to opt for an electric bus on sound perceptions of the TCO, the performance of alternative vehicles and to achieve global environmental targets and healthier life in general. Regulation with local consent and leadership of new alternative transportation services should strongly support the future innovations in the transportation sector with the aim to improve air quality which will improve the quality of life. It is important to recognize that what is suitable for one region (electric, hydrogen or natural- i.e. biomethane gas), city or rural area will not obligatorily be appropriate for another. The selection depends on speed, total passenger capacity, range, power, battery capacity and charging time. Where local leaders are keen to lead the way in transportation innovation, the regulatory system should support them to do so in the most appropriate manner. In addition, it is crucial to make an analysis based on the local area needs in order to opt the best type of alternative bus.

In conclusion, even with currently higher TCO, BEB will be in the long-term, economically feasible and competitive with DB. It is proven that BEB and FCEB present the most promising solution in the future for sustainable transportation and environmental benefits. Otherwise, models like NGB would be good transition model in the EU countries with a weaker economy.

This thesis provides a framework for the planning and evaluation of the electric bus system. Several aspects could be considered for further analysis:

- Detailed analysis of WTT emissions including different fuel production technologies and their influence on GHG emission and total air pollution;
- Infrastructure costs for charging stations in urban and rural areas with in-depth data analysis based on each EU country and their possibilities.

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Addendum

Addendum A- Economical Calculations

Table A1: Scenario for TCO for diesel bus in referent year 2018 without CO_2 increasing

year	Cpurchase	Crep_y	Cfuel_y	Cmaint_y	Cco2_y	1 + d_rate	(1+d_rate)^y	Cop_y	(C_(op_y)+C_(rep_y))*(1+d_rate)^(-y)	TCO (Euro)
2018	170000	0	0,52	0,18	0,028	1,014	1,01	43680	43076,92	213076,92
2019							1,03	43680	42482,17	255559,10
2020							1,04	43680	41895,63	297454,73
2021							1,06	43680	41317,19	338771,92
2022							1,07	43680	40746,74	379518,66
2023							1,09	43680	40184,16	419702,82
2024							1,10	43680	39629,35	459332,17
2025							1,12	43680	39082,20	498414,37
2026							1,13	43680	38542,60	536956,97
2027							1,15	43680	38010,46	574967,43
2028							1,17	43680	37485,66	612453,09
2029							1,18	43680	36968,10	649421,19
2030							1,20	43680	36457,70	685878,88
2031							1,21	43680	35954,33	721833,22
2032							1,23	43680	35457,92	757291,14

Table A2: Scenario for TCO for natural gas bus in referent year 2018 without CO_2 increasing

year	Cpurchase	Crep_y	Cfuel_y	Cmaint_y	Cco2_y	1 + d_rate	(1+d_rate)^y	Cop_y	(C_(op_y)+C_(rep_y))*(1+d_rate)^(-y)	TCO (Euro)
2018	240000	0	0,37	0,22	0,03	1,01	1,01	37020,00	36508,88	276508,88
2019							1,03	37020,00	36004,81	312513,68
2020							1,04	37020,00	35507,70	348021,38
2021							1,06	37020,00	35017,46	383038,84
2022							1,07	37020,00	34533,98	417572,82
2023							1,09	37020,00	34057,18	451630,00
2024							1,10	37020,00	33586,96	485216,96
2025							1,12	37020,00	33123,24	518340,20
2026							1,13	37020,00	32665,91	551006,12
2027							1,15	37020,00	32214,91	583221,02
2028							1,17	37020,00	31770,12	614991,15
2029							1,18	37020,00	31331,48	646322,63
2030							1,20	37020,00	30898,90	677221,53
2031							1,21	37020,00	30472,29	707693,81
2032							1,23	37020,00	30051,56	737745,38

Table A3: Scenario for TCO for fuel-cell-electric bus in referent year 2018 without CO_2 increasing and with battery and fuel cell replacement

year	Cpurchase	Crep_y	Cfuel_y	Cmaint_y	Cco2_y	1 + d_rate	(1+d_rate)^y	Cop_y	(C_(op_y)+C_(rep_y))*(1+d_rate)^(-y)	TCO (Euro)
2018	1000000		0,68	0,28	0,02	1,04	1,04	59040,00	56769,23	1056769,23
2019							1,08	59040,00	54585,80	1111355,03
2020							1,12	59040,00	52486,35	1163841,37
2021							1,17	59040,00	50467,64	1214309,01
2022							1,22	59040,00	48526,58	1262835,59
2023							1,27	59040,00	46660,17	1309495,76
2024		109000					1,32	59040,00	127696,59	1437192,35
2025							1,37	59040,00	43139,95	1480332,30
2026							1,42	59040,00	41480,72	1521813,02
2027							1,48	59040,00	39885,31	1561698,33
2028							1,54	59040,00	38351,26	1600049,59
2029							1,60	59040,00	36876,21	1636925,80
2030							1,67	59040,00	35457,89	1672383,69
2031							1,73	59040,00	34094,13	1706477,82
2032							1,80	59040,00	32782,82	1739260,64

Table A4: Scenario for TCO for battery-electric bus in referent year 2018 without CO_2 increasing and with battery replacement

year	Cpurchase	Crep_y	Cfuel_y	Cmaint_y	Cco2_y	1 + d_rate	(1+d_rate)^y	Cop_y	(C_(op_y)+C_(rep_y))*(1+d_rate)^(-y)	TCO (Euro)
2018	313000		0,32	0,28	0,018	1,04	1,04	37080,00	35653,85	348653,85
2019							1,08	37080,00	34282,54	382936,39
2020							1,12	37080,00	32963,98	415900,38
2021							1,17	37080,00	31696,14	447596,51
2022							1,22	37080,00	30477,06	478073,57
2023							1,27	37080,00	29304,86	507378,43
2024		54000					1,32	37080,00	69213,31	576591,75
2025							1,37	37080,00	27093,99	603685,74
2026							1,42	37080,00	26051,92	629737,66
2027							1,48	37080,00	25049,92	654787,58
2028							1,54	37080,00	24086,46	678874,04
2029							1,60	37080,00	23160,06	702034,10
2030							1,67	37080,00	22269,29	724303,38
2031							1,73	37080,00	21412,78	745716,16
2032							1,80	37080,00	20589,21	766305,37

Table A5: Scenario for TCO for diesel bus in referent year 2018 with annually CO_2 increasing

year	Cpurchase	Crep_y	Cfuel_y	Cmaint_y	Cco2_y	1 + d_rate	(1+d_rate)^y	Cop_y	(C_(op_y)+C_(rep_y))*(1+d_rate)^(-y)	TCO (Euro)
2018	170000	0	0,52	0,18	0,03	1,01	1,01	43680,00	43076,92	213076,92
2019					0,03		1,03	44016,00	42808,96	255885,88
2020					0,04		1,04	44419,20	42604,64	298490,52
2021					0,05		1,06	44903,04	42474,07	340964,59
2022					0,06		1,07	45483,65	42429,27	383393,86
2023					0,07		1,09	46180,38	42484,43	425878,28
2024					0,08		1,10	47016,45	42656,40	468534,68
2025					0,10		1,12	48019,74	42965,14	511499,82
2026					0,12		1,13	49223,69	43434,28	554934,10
2027					0,14		1,15	50668,43	44091,81	599025,90
2028					0,17		1,17	52402,12	44970,87	643996,78
2029					0,21		1,18	54482,54	46110,72	690107,50
2030					0,25		1,20	56979,05	47557,80	737665,30
2031					0,30		1,21	59974,86	49367,13	787032,43
2032					0,36		1,23	63569,83	51603,81	838636,23

Table A6: Scenario for TCO for natural gas bus in referent year 2018 with annually CO_2 increasing

year	Cpurchase	Crep_y	Cfuel_y	Cmaint_y	Cco2_y	1 + d_rate	(1+d_rate)^y	Cop_y	(C_(op_y)+C_(rep_y))*(1+d_rate)^(-y)	TCO (Euro)
2018	240000	0	0,37	0,22	0,03	1,01	1,01	37020,00	36508,88	276508,88
2019					0,03		1,03	37344,00	36319,92	312828,80
2020					0,04		1,04	37732,80	36191,38	349020,18
2021					0,05		1,06	38199,36	36133,02	385153,20
2022					0,06		1,07	38759,23	36156,42	421309,62
2023					0,07		1,09	39431,08	36275,29	457584,91
2024					0,08		1,10	40237,29	36505,90	494090,81
2025					0,10		1,12	41204,75	36867,50	530958,31
2026					0,12		1,13	42365,70	37382,89	568341,20
2027					0,14		1,15	43758,84	38079,07	606420,26
2028					0,17		1,17	45430,61	38988,01	645408,28
2029					0,20		1,18	47436,74	40147,58	685555,85
2030					0,24		1,20	49844,08	41602,57	727158,43
2031					0,29		1,21	52732,90	43406,05	770564,48
2032					0,35		1,23	56199,48	45620,81	816185,28

Table A7: Scenario for TCO for fuel-cell-electric bus in referent year 2018 with annually CO_2 increasing and with battery and fuel cell replacement

year	Cpurchase	Crep_y	Cfuel_y	Cmaint_y	Cco2_y	1 + d_rate	(1+d_rate)^y	Cop_y	(C_(op_y)+C_(rep_y))*(1+d_rate)^(-y)	TCO (Euro)
2018	1000000		0,68	0,28	0,02	1,04	1,04	59040,00	56769,23	1056769,23
2019					0,03		1,08	59328,00	54852,07	1111621,30
2020					0,03		1,12	59673,60	53049,61	1164670,91
2021					0,04		1,17	60088,32	51363,75	1216034,66
2022					0,05		1,22	60585,98	49797,26	1265831,93
2023					0,06		1,27	61183,18	48353,96	1314185,88
2024		109000			0,07		1,32	61899,82	129869,82	1444055,70
2025					0,09		1,37	62759,78	45857,96	1489913,65
2026					0,10		1,42	63791,74	44819,23	1534732,88
2027					0,12		1,48	65030,08	43931,99	1578664,88
2028					0,15		1,54	66516,10	43207,59	1621872,47
2029					0,18		1,60	68299,32	42659,55	1664532,02
2030					0,21		1,67	70439,18	42303,95	1706835,97
2031					0,26		1,73	73007,02	42159,74	1748995,71
2032					0,31		1,80	76088,43	42249,20	1791244,91

Table A8: Scenario for TCO for battery-electric bus in referent year 2018 with annually CO_2 increasing and with battery and fuel cell replacement

year	Cpurchase	Crep_y	Cfuel_y	Cmaint_y	Cco2_y	1 + d_rate	(1+d_rate)^y	Cop_y	(C_(op_y)+C_(rep_y))*(1+d_rate)^(-y)	TCO (Euro)
2018	313000		0,32	0,28	0,02	1,04	1,04	37080,00	35653,85	348653,85
2019					0,02		1,08	37296,00	34482,25	383136,09
2020					0,03		1,12	37555,20	33386,44	416522,53
2021					0,03		1,17	37866,24	32368,22	448890,75
2022					0,04		1,22	38239,49	31430,07	480320,82
2023					0,04		1,27	38687,39	30575,20	510896,03
2024		54000			0,05		1,32	39224,86	70843,23	581739,26
2025					0,06		1,37	39869,84	29132,50	610871,76
2026					0,08		1,42	40643,80	28555,80	639427,55
2027					0,09		1,48	41572,56	28084,93	667512,49
2028					0,11		1,54	42687,08	27728,71	695241,20
2029					0,13		1,60	44024,49	27497,57	722738,77
2030					0,16		1,67	45629,39	27403,83	750142,59
2031					0,19		1,73	47555,27	27461,98	777604,57
2032					0,23		1,80	49866,32	27689,00	805293,57

Table A9: Scenario for TCO for diesel bus in year 2030 without annually CO_2 increasing

year	Cpurchase	Crep_y	Cfuel_y	Cmaint_y	Cco2_y	1 + d_rate	(1+d_rate)^y	Cop_y	(C_(op_y)+C_(rep_y))*(1+d_rate)^(-y)	TCO (Euro)
2030	160000	0	0,61	0,18	0,204	1,03	1,03	59640,00	57902,91	217902,91
2031							1,06	59640,00	56216,42	274119,33
2032							1,09	59640,00	54579,05	328698,38
2033							1,13	59640,00	52989,37	381687,75
2034							1,16	59640,00	51445,99	433133,74
2035							1,19	59640,00	49947,56	483081,30
2036							1,23	59640,00	48492,78	531574,08
2037							1,27	59640,00	47080,37	578654,44
2038							1,30	59640,00	45709,09	624363,54
2039							1,34	59640,00	44377,76	668741,30
2040							1,38	59640,00	43085,20	711826,50
2041							1,43	59640,00	41830,30	753656,80
2042							1,47	59640,00	40611,94	794268,74
2043							1,51	59640,00	39429,07	833697,80
2044							1,56	59640,00	38280,65	871978,45

Table A10: Scenario for TCO for natural gas bus in year 2030 without annually CO_2 increasing

year	Cpurchase	Crep_y	Cfuel_y	Cmaint_y	Cco2_y	1 + d_rate	(1+d_rate)^y	Cop_y	(C_(op_y)+C_(rep_y))*(1+d_rate)^(-y)	TCO (Euro)
2030	246000	0	0,45	0,22	0,196	1,03	1,03	51960,00	50446,60	296446,60
2031							1,06	51960,00	48977,28	345423,89
2032							1,09	51960,00	47550,76	392974,65
2033							1,13	51960,00	46165,79	439140,43
2034							1,16	51960,00	44821,15	483961,59
2035							1,19	51960,00	43515,68	527477,27
2036							1,23	51960,00	42248,23	569725,50
2037							1,27	51960,00	41017,70	610743,21
2038							1,30	51960,00	39823,01	650566,22
2039							1,34	51960,00	38663,12	689229,34
2040							1,38	51960,00	37537,01	726766,35
2041							1,43	51960,00	36443,70	763210,05
2042							1,47	51960,00	35382,23	798592,28
2043							1,51	51960,00	34351,68	832943,96
2044							1,56	51960,00	33351,15	866295,11

Table A11: Scenario for TCO for fuel-cell-electric bus in year 2030 without annually CO_2 increasing and with battery and fuel cell replacement

year	Cpurchase	Crep_y	Cfuel_y	Cmaint_y	Cco2_y	1 + d_rate	(1+d_rate)^y	Cop_y	(C_(op_y)+C_(rep_y))*(1+d_rate)^(-y)	TCO (Euro)
2030	320000		0,45	0,28	0,115	1,03	1,03	50700,00	49223,30	369223,30
2031							1,06	50700,00	47789,61	417012,91
2032							1,09	50700,00	46397,68	463410,60
2033							1,13	50700,00	45046,29	508456,89
2034							1,16	50700,00	43734,27	552191,15
2035							1,19	50700,00	42460,45	594651,61
2036		43500					1,23	50700,00	76593,22	671244,83
2037							1,27	50700,00	40023,05	711267,87
2038							1,30	50700,00	38857,33	750125,20
2039							1,34	50700,00	37725,56	787850,76
2040							1,38	50700,00	36626,76	824477,52
2041							1,43	50700,00	35559,96	860037,48
2042							1,47	50700,00	34524,23	894561,72
2043							1,51	50700,00	33518,67	928080,39
2044							1,56	50700,00	32542,40	960622,79

Table A12: Scenario for TCO for battery-electric bus in year 2030 without annually CO_2 increasing and with battery replacement

year	Cpurchase	Crep_y	Cfuel_y	Cmaint_y	Cco2_y	1 + d_rate	(1+d_rate)^y	Cop_y	(C_(op_y)+C_(rep_y))*(1+d_rate)^(-y)	TCO (Euro)
2030	220000		0,34	0,28	0,098	1,03	1,03	43080,00	41825,24	261825,24
2031							1,06	43080,00	40607,03	302432,27
2032							1,09	43080,00	39424,30	341856,58
2033							1,13	43080,00	38276,02	380132,60
2034							1,16	43080,00	37161,19	417293,79
2035							1,19	43080,00	36078,82	453372,61
2036		21000					1,23	43080,00	52102,90	505475,51
2037							1,27	43080,00	34007,75	539483,26
2038							1,30	43080,00	33017,23	572500,49
2039							1,34	43080,00	32055,57	604556,06
2040							1,38	43080,00	31121,91	635677,97
2041							1,43	43080,00	30215,45	665893,41
2042							1,47	43080,00	29335,38	695228,80
2043							1,51	43080,00	28480,96	723709,75
2044							1,56	43080,00	27651,41	751361,17

Table A13: Scenario for TCO for diesel bus in year 2030 with annually CO_2 increasing

year	Cpurchase	Crep_y	Cfuel_y	Cmaint_y	Cco2_y	1 + d_rate	(1+d_rate)^y	Cop_y	(C_(op_y)+C_(rep_y))*(1+d_rate)^(-y)	TCO (Euro)
2030	160000	0	0,61	0,18	0,20	1,03	1,03	59640,00	57902,91	217902,91
2031					0,24		1,06	62088,00	58523,89	276426,81
2032					0,29		1,09	65025,60	59507,64	335934,44
2033					0,35		1,13	68550,72	60906,43	396840,87
2034					0,42		1,16	72780,86	62781,41	459622,28
2035					0,51		1,19	77857,04	65204,04	524826,32
2036					0,61		1,23	83948,44	68257,77	593084,09
2037					0,73		1,27	91258,13	72040,01	665124,11
2038					0,88		1,30	100029,76	76664,48	741788,59
2039					1,05		1,34	110555,71	82263,83	824052,42
2040					1,26		1,38	123186,85	88992,80	913045,22
2041					1,52		1,43	138344,22	97031,86	1010077,08
2042					1,82		1,47	156533,07	106591,40	1116668,48
2043					2,18		1,51	178359,68	117916,76	1234585,24
2044					2,62		1,56	204551,62	131293,90	1365879,15

Table A14: Scenario for TCO for natural gas bus in year 2030 with annually CO_2 increasing

year	Cpurchase	Crep_y	Cfuel_y	Cmaint_y	Cco2_y	1 + d_rate	(1+d_rate)^y	Cop_y	(C_(op_y)+C_(rep_y))*(1+d_rate)^(-y)	TCO (Euro)
2030	246000	0	0,45	0,22	0,20	1,03	1,03	51960,00	50446,60	296446,60
2031					0,24		1,06	54312,00	51194,27	347640,87
2032					0,28		1,09	57134,40	52286,07	399926,94
2033					0,34		1,13	60521,28	53772,37	453699,31
2034					0,41		1,16	64585,54	55712,05	509411,36
2035					0,49		1,19	69462,64	58173,87	567585,23
2036					0,59		1,23	75315,17	61238,13	628823,36
2037					0,70		1,27	82338,21	64998,54	693821,90
2038					0,84		1,30	90765,85	69564,46	763386,37
2039					1,01		1,34	100879,02	75063,46	838449,83
2040					1,21		1,38	113014,82	81644,31	920094,14
2041					1,46		1,43	127577,78	89480,49	1009574,63
2042					1,75		1,47	145053,34	98774,27	1108348,90
2043					2,10		1,51	166024,01	109761,43	1218110,33
2044					2,52		1,56	191188,81	122716,82	1340827,15

Table A15: Scenario for TCO for fuel-cell-electric bus in year 2030 with annually CO_2 increasing and without battery and fuel cell replacement

year	Cpurchase	Crep_y	Cfuel_y	Cmaint_y	Cco2_y	1 + d_rate	(1+d_rate)^y	Cop_y	(C_(op_y)+C_(rep_y))*(1+d_rate)^(-y)	TCO (Euro)
2030	320000		0,45	0,28	0,12	1,03	1,03	50700,00	49223,30	369223,30
2031					0,14		1,06	52080,00	49090,39	418313,70
2032					0,17		1,09	53736,00	49176,05	467489,75
2033					0,20		1,13	55723,20	49509,34	516999,09
2034					0,24		1,16	58107,84	50124,33	567123,42
2035					0,29		1,19	60969,41	51060,92	618184,34
2036					0,34		1,23	64403,29	52365,77	670550,11
2037					0,41		1,27	68523,95	54093,44	724643,55
2038					0,49		1,30	73468,74	56307,67	780951,22
2039					0,59		1,34	79402,48	59082,91	840034,12
2040					0,71		1,38	86522,98	62506,04	902540,16
2041					0,85		1,43	95067,58	66678,49	969218,65
2042					1,03		1,47	105321,09	71718,54	1040937,19
2043					1,23		1,51	117625,31	77764,19	1118701,38
2044					1,48		1,56	132390,37	84976,34	1203677,72

Table A16: Scenario for TCO for battery-electric bus in year 2030 with annually CO_2 increasing and without battery and fuel cell replacement

year	Cpurchase	Crep_y	Cfuel_y	Cmaint_y	Cco2_y	1 + d_rate	(1+d_rate)^y	Cop_y	(C_(op_y)+C_(rep_y))*(1+d_rate)^(-y)	TCO (Euro)
2030	220000		0,34	0,28	0,10	1,03	1,03	43080,00	41825,24	261825,24
2031					0,12		1,06	44256,00	41715,52	303540,77
2032					0,14		1,09	45667,20	41791,96	345332,72
2033					0,17		1,13	47360,64	42079,32	387412,04
2034					0,20		1,16	49392,77	42606,64	430018,68
2035					0,24		1,19	51831,32	43407,92	473426,59
2036					0,29		1,23	54757,59	44522,93	517949,52
2037					0,35		1,27	58269,10	45998,17	563947,69
2038					0,42		1,30	62482,92	47887,96	611835,65
2039					0,51		1,34	67539,51	50255,74	662091,38
2040					0,61		1,38	73607,41	53175,56	715266,94
2041					0,73		1,43	80888,89	56733,84	772000,78
2042					0,87		1,47	89626,67	61031,40	833032,19
2043					1,05		1,51	100112,00	66185,83	899218,01
2044					1,26		1,56	112694,41	72334,25	971552,26

Table A17: Scenario for TCO for fuel-cell-electric bus in year 2030 with annually CO_2 increasing and with battery and fuel cell replacement

year	Cpurchase	Crep_y	Cfuel_y	Cmaint_y	Cco2_y	1 + d_rate	(1+d_rate)^y	Cop_y	(C_(op_y)+C_(rep_y))*(1+d_rate)^(-y)	TCO (Euro)
2030	320000		0,45	0,28	0,12	1,03	1,03	50700,00	49223,30	369223,30
2031					0,14		1,06	52080,00	49090,39	418313,70
2032					0,17		1,09	53736,00	49176,05	467489,75
2033					0,20		1,13	55723,20	49509,34	516999,09
2034					0,24		1,16	58107,84	50124,33	567123,42
2035					0,29		1,19	60969,41	51060,92	618184,34
2036		43500			0,34		1,23	64403,29	87735,25	705919,59
2037					0,41		1,27	68523,95	54093,44	760013,03
2038					0,49		1,30	73468,74	56307,67	816320,70
2039					0,59		1,34	79402,48	59082,91	875403,60
2040					0,71		1,38	86522,98	62506,04	937909,65
2041					0,85		1,43	95067,58	66678,49	1004588,13
2042					1,03		1,47	105321,09	71718,54	1076306,67
2043					1,23		1,51	117625,31	77764,19	1154070,86
2044					1,48		1,56	132390,37	84976,34	1239047,20

Table A18: Scenario for TCO for battery-electric bus in year 2030 with annually CO_2 increasing and with battery replacement

year	Cpurchase	Crep_y	Cfuel_y	Cmaint_y	Cco2_y	1 + d_rate	(1+d_rate)^y	Cop_y	(C_(op_y)+C_(rep_y))*(1+d_rate)^(-y)	TCO (Euro)
2030	220000		0,34	0,28	0,10	1,03	1,03	43080,00	41825,24	261825,24
2031					0,12		1,06	44256,00	41715,52	303540,77
2032					0,14		1,09	45667,20	41791,96	345332,72
2033					0,17		1,13	47360,64	42079,32	387412,04
2034					0,20		1,16	49392,77	42606,64	430018,68
2035					0,24		1,19	51831,32	43407,92	473426,59
2036		21000			0,29		1,23	54757,59	61597,85	535024,44
2037					0,35		1,27	58269,10	45998,17	581022,61
2038					0,42		1,30	62482,92	47887,96	628910,57
2039					0,51		1,34	67539,51	50255,74	679166,30
2040					0,61		1,38	73607,41	53175,56	732341,86
2041					0,73		1,43	80888,89	56733,84	789075,71
2042					0,87		1,47	89626,67	61031,40	850107,11
2043					1,05		1,51	100112,00	66185,83	916292,94
2044					1,26		1,56	112694,41	72334,25	988627,19

Addendum B – GHG Calculations

Table B1: GHG_{WTW} for all bus types for referent year 2018

Operation	GHGwtw (kg CO_2/km)	GHG wtw (kg CO_2 per year)
Diesel Bus	(0,4353l/km*10,4kWh/l*57,58g/kWh)+1,15kg/km=1,411 kg/km	1,411kg/km*60000km=84660 kg CO_2
Natural Gas Bus	(0,5694l/km*10,4kWh/l*28,6g/kWh)+1,18kg/km=1,349 kg/km	1,349kg/km*60000km=80940 kg CO_2
Electric Fuel Cell Bus	(0,2997l/km*10,4kWh/l*380,8g/kWh)+0kg/km=1,186 kg/km	1,186kg/km*60000km=71160 kg CO_2
Electric Battery Bus	(0,1556l/km*10,4kWh/l*583g/kWh)+0kg/km=0,944 kg/km	0,944kg/km*60000km=56640 kg CO_2

Table B2: Accumulative GHG from referent year 2018

	Diesel Bus			Natual Gas Bus			Electric Fuel Cell Bus			Electric Battery Bus		
Year/kg CO_2	GHGmanuf	GHGwtw	GHGtotal	GHGmanuf	GHGwtw	GHGtotal	GHGmanuf	GHGwtw	GHGtotal	GHGmanuf	GHGwtw	GHGtotal
2018	2547,2	84660	87207,2	3034,6	80940	83974,6	4552	71160	75712	2812,2	56640	58615,16
2019			171867,2			164914,6			146872			115255,16
2020			256527,2			245854,6			218032			171895,16
2021			341187,2			326794,6			289192			228535,16
2022			425847,2			407734,6			360352			285175,16
2023			510507,2			488674,6			431512			341815,16
2024			595167,2			569614,6			502672			398455,16
2025			679827,2			650554,6			573832			455095,16
2026			764487,2			731494,6			644992			511735,16
2027			849147,2			812434,6			716152			568375,16
2028			933807,2			893374,6			787312			625015,16
2029			1018467,2			974314,6			858472			681655,16
2030			1103127,2			1055254,6			929632			738295,16
2031			1187787,2			1136194,6			1000792			794935,16
2032			1272447,2			1217134,6			1071952			851575,16

Table B3: GHG_{WTW} for all bus types for year 2030

Operation	GHGwtw (kg CO_2/km)	GHG wtw (kg CO_2 per year)
Diesel Bus	(0,4353l/km*10,4kWh/l*51,29g/kWh)+0,89kg/km=1,12 kg/km	1,12kg/km*60000km=67800 kg CO_2
Natural Gas Bus	(0,5694l/km*10,4kWh/l*25,38g/kWh)+0,93kg/km=1,08 kg/km	1,08kg/km*60000km=64800 kg CO_2
Electric Fuel Cell Bus	(0,2997l/km*10,4kWh/l*337,94g/kWh)+0kg/km=1,05 kg/km	1,05kg/km*60000km=63000 kg CO_2
Electric Battery Bus	(0,1556l/km*10,4kWh/l*279,68g/kWh)+0kg/km=0,45 kg/km	0,45kg/km*60000km=27000 kg CO_2

Table B4: Accumulative GHG from year 2030

	Diesel Bus			Natural Gas Bus			Electric Fuel Cell Bus			Electric Battery Bus		
Year/kg CO_2	GHGmanuf	GHGwtw	GHGtotal	GHGmanuf	GHGwtw	GHGtotal	GHGmanuf	GHGwtw	GHGtotal	GHGmanuf	GHGwtw	GHGtotal
2030	2547,2	67800	70347,2	3034,6	64800	67834,6	4552	63000	67552	2812,2	27000	29812,2
2031			138147,2			132634,6			130552			56812,2
2032			205947,2			197434,6			193552			83812,2
2033			273747,2			262234,6			256552			110812,2
2034			341547,2			327034,6			319552			137812,2
2035			409347,2			391834,6			382552			164812,2
2036			477147,2			456634,6			445552			191812,2
2037			544947,2			521434,6			508552			218812,2
2038			612747,2			586234,6			571552			245812,2
2039			680547,2			651034,6			634552			272812,2
2040			748347,2			715834,6			697552			299812,2
2041			816147,2			780634,6			760552			326812,2
2042			883947,2			845434,6			823552			353812,2
2043			951747,2			910234,6			886552			380812,2
2044			1019547,2			975034,6			949552			407812,2

Addendum C – Air Pollution Calculations

Table C1: $NO_{X\,WTW}$ for all bus types for referent year 2018

Operation	NOx wtw (g/km)	NOx wtw (kg NOx per year)
Diesel Bus	(0,4353l/km*10,4kWh/l*0,141g/kWh)+12,94g/km=13,58g/km	13,58g/km*60000km=814,8 kg NOx
Natural Gas Bus	(0,5694l/km*10,4kWh/l*0,162g/kWh)+0,66g/km=1,62g/km	1,62g/km*60000km=97,2 kg NOx
Electric Fuel Cell Bus	(0,2997l/km*10,4kWh/l*0,326g/kWh)+0g/km=1,01g/km	1,01g/km*60000km=60,6 kg NOx
Electric Battery Bus	(0,1556l/km*10,4kWh/l*0,6 g/kWh)+0g/km=0,97g/km	0,97g/km*60000km=58,2 kg NOx

Table C2: Accumulative NO_X from referent year 2018

	Diesel Bus			Natural Gas Bus			Electric Fuel Cell Bus			Electric Battery Bus		
Year/kg NOx	NOx manuf	NOx wtw	NOx total	NOx manuf	NOx wtw	NOx total	NOx manuf	NOx wtw	NOx total	NOx manuf	NOx wtw	NOx total
2018	4,11	814,8	818,91	4,89	97,2	102,09	7,131	60,6	67,731	4,737	58,2	62,937
2019			1633,71			199,29			126,00023			121,137
2020			2448,51			296,49			184,26946			179,337
2021			3263,31			393,69			242,53869			237,537
2022			4078,11			490,89			300,80792			295,737
2023			4892,91			588,09			359,07715			353,937
2024			5707,71			685,29			417,34638			412,137
2025			6522,51			782,49			475,61561			470,337
2026			7337,31			879,69			533,88484			528,537
2027			8152,11			976,89			592,15407			586,737
2028			8966,91			1074,09			650,4233			644,937
2029			9781,71			1171,29			708,69253			703,137
2030			10596,51			1268,49			766,96176			761,337
2031			11411,31			1365,69			825,23099			819,537
2032			12226,11			1462,89			883,50022			877,737

Table C3: NO_{XWTW} for all bus types for year 2030

Operation	NOx wtw (g/km)	NOx wtw (kg NOx per year)
Diesel Bus	(0,4353l/km*10,4kWh/l*0,14g/kWh)+10,22g/km=10,85g/km	10,85g/km*60000km=651 kg NOx
Natural Gas Bus	(0,5694l/km*10,4kWh/l*0,16g/kWh)/1000km+0,52g/km=1,47g/km	1,47g/km*60000km=88,2 kg NOx
Electric Fuel Cell Bus	(0,2997l/km*10,4kWh/l*0,18g/kWh)/1000km+0g/km=0,56g/km	0,56g/km*60000km=33,6 kg NOx
Electric Battery Bus	(0,1556l/km*10,4kWh/l*0,44 g/kWh)+0g/km=0,71g/km	0,71g/km*60000km=42,6 kg NOx

Table C4: Accumulative NO_X from year 2030

	Diesel Bus			Natural Gas Bus			Electric Fuel Cell Bus			Electric Battery Bus		
Year/kg NOx	NOx manuf	NOx wtw	NOx total	NOx manuf	NOx wtw	NOx total	NOx manuf	NOx wtw	NOx total	NOx manuf	NOx wtw	NOx total
2030	4,11	651	655,11	4,89	88,2	93,09	7,131	33,6	40,731	4,737	42,6	47,337
2031			1306,11			181,29			73,0387			89,937
2032			1957,11			269,49			105,3464			132,537
2033			2608,11			357,69			137,6541			175,137
2034			3259,11			445,89			169,9618			217,737
2035			3910,11			534,09			202,2695			260,337
2036			4561,11			622,29			234,5772			302,937
2037			5212,11			710,49			266,8849			345,537
2038			5863,11			798,69			299,1926			388,137
2039			6514,11			886,89			331,5003			430,737
2040			7165,11			975,09			363,808			473,337
2041			7816,11			1063,29			396,1157			515,937
2042			8467,11			1151,49			428,4234			558,537
2043			9118,11			1239,69			460,7311			601,137
2044			9769,11			1327,89			493,0388			643,737

Table C5: PM_{WTW} for all bus types for referent year 2018

Operation	PM wtw (g/km)	PM wtw (kg PM per year)
Diesel Bus	(0,4353l/km*10,4kWh/l*0,006g/kWh)+0,24g/km=0,27g/km	0,27g/km*60000km=16,2 kg PM
Natural Gas Bus	(0,5694l/km*10,4kWh/l*0,003g/kWh)+0,02g/km=0,04g/km	0,04g/km*60000km=2,4 kg PM
Electric Fuel Cell Bus	(0,2997l/km*10,4kWh/l*0,028g/kWh)+0g/km=0,09g/km	0,09g/km*60000km=5,4 kg PM
Electric Battery Bus	(0,1556l/km*10,4kWh/l*0,14g/kWh)+0g/km=0,23g/km	0,23g/km*60000km=3,2 kg PM

Table C6: Accumulative PM from referent year 2018

	Diesel Bus			Natural Gas Bus			Electric Fuel Cell Bus			Electric Battery Bus		
Year/kg PM	PM manuf	PM wtw	PM total	PM manuf	PM wtw	PM total	PM manuf	PM wtw	PM total	PM manuf	PM wtw	PM total
2018	1,21	16,2	17,41	1,32	2,4	3,72	2,68	5,4	8,08	2,12	13,8	15,92
2019			33,61			6,12			13,48			29,72
2020			49,81			8,52			18,88			43,52
2021			66,01			10,92			24,28			57,32
2022			82,21			13,32			29,68			71,12
2023			98,41			15,72			35,08			84,92
2024			114,61			18,12			40,48			98,72
2025			130,81			20,52			45,88			112,52
2026			147,01			22,92			51,28			126,32
2027			163,21			25,32			56,68			140,12
2028			179,41			27,72			62,08			153,92
2029			195,61			30,12			67,48			167,72
2030			211,81			32,52			72,88			181,52
2031			228,01			34,92			78,28			195,32
2032			244,21			37,32			83,68			209,12

Table C7: PM_{WTW} for all bus types for year 2030

Operation	PM wtw (g/km)	PM wtw (kg PM per year)
Diesel Bus	(0,4353l/km*10,4kWh/l*0,008g/kWh)+0,19g/km=0,23g/km	0,23g/km*60000km=13,8 kg PM
Natural Gas Bus	(0,5694l/km*10,4kWh/l*0,004g/kWh)+0,01g/km=0,034g/km	0,034g/km*60000km=1,8 kg PM
Electric Fuel Cell Bus	(0,2997l/km*10,4kWh/l*0,012g/kWh)+0g/km=0,04g/km	0,04g/km*60000km=2,4 kg PM
Electric Battery Bus	(0,1556l/km*10,4kWh/l*0,083g/kWh)+0g/km=0,13g/km	0,13g/km*60000km=7,8 kg PM

Table C8: Accumulative PM from year 2030

	Diesel Bus			Natural Gas Bus			Electric Fuel Cell Bus			Electric Battery Bus		
Year/kg PM	PM manuf	PM wtw	PM total	PM manuf	PM wtw	PM total	PM manuf	PM wtw	PM total	PM manuf	PM wtw	PM total
2030	1,21	13,8	15,01	1,32	1,8	3,12	2,68	2,4	5,08	2,12	7,8	9,92
2031			28,81			4,92			7,48			17,72
2032			42,61			6,72			9,88			25,52
2033			56,41			8,52			12,28			33,32
2034			70,21			10,32			14,68			41,12
2035			84,01			12,12			17,08			48,92
2036			97,81			13,92			19,48			56,72
2037			111,61			15,72			21,88			64,52
2038			125,41			17,52			24,28			72,32
2039			139,21			19,32			26,68			80,12
2040			153,01			21,12			29,08			87,92
2041			166,81			22,92			31,48			95,72
2042			180,61			24,72			33,88			103,52
2043			194,41			26,52			36,28			111,32
2044			208,21			28,32			38,68			119,12