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***Potential Solutions for Electric Vehicles in
Bus and Delivery Traffic***

Master's thesis submitted for approval for the degree of Master of Science.

Espoo, 1 November 2010

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Preface

This Master's thesis was made at the Department of Electrical Engineering of the Aalto University School of Science and Technology. The thesis was carried out in cooperation with the research project SIMBe (Smart Infrastructures for Electric Mobility in Built Environments).

There are a few individuals whose support was invaluable to me during the writing of this thesis. Firstly, I want to express my gratitude to my supervisor, Professor Matti Lehtonen. He provided me with a lot of useful information, as well as an insight into the topic of my work. I also want to thank Eero Saarijärvi for instructing, as well as William Martin and Eva Lönnholm for proofreading my work. An additional thank you goes to my colleagues who commented my work during the writing process.

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<p>The Finnish traffic planning organisation aims for more sustainable vehicular solutions. This thesis presents the most applicable electric vehicle technologies suitable for colder climates, such as in Finland. The discussed vehicle technologies contribute to sustainable development. Both public and private sectors are taken into account. The vehicle electrification in public passenger transport is mainly addressed in the section for the bus traffic, whereas the private sector comes into play in the context of the delivery traffic. Rail traffic, however, is not discussed in the thesis. The literature for the study is gathered from various Internet sources, scientific articles and books. Additionally, two interviews were carried out to gain information about the attitudes towards vehicle electrification in the Helsinki metropolitan area. Thus, the used material covers the present knowledge about the discussed electric vehicle technologies, their prevalence and typical usage, as well as the level of interest shown towards them.</p> <p>The major technologies to be considered in vehicle electrification are trolley buses, as well as vehicles based on battery and hydrogen fuel cell technologies. A comparison of these basic technologies is included in the thesis. The sustainability of the different vehicle technologies is largely assessed by the production of the used electricity or hydrogen. For making electric vehicles a more viable alternative for bus and delivery traffic, there is a need for promoting more low-carbon electricity and hydrogen production. In general, it was discovered that the current battery technologies alone do not provide an economical alternative for powering buses. Along with fuel cells, batteries are still a high-cost solution to be further developed. Batteries, however, can reasonably be used for the regeneration of vehicle braking power, as an APU or for extending the range of the vehicle. Currently, the most applicable solution for buses seems to be the trolley bus which provides the lowest acquisition price and by far the longest life cycle. Trolley buses have also been used in colder climates with success. In the delivery vehicle sector, electric vehicles running on pure batteries will be promoted more strongly. In order to find out the most applicable, practical electric vehicle technologies, future studies within the subject matter should consider possible combinations of the discussed vehicle technologies.</p>	
<p>Keywords: battery, battery-electric bus, electric vehicle, energy storage, fuel cell, plug-in hybrid electric vehicle, trolley bus</p>	

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<p>Kestävän kehityksen mukaiset ajoneuvoratkaisut ovat osa suomalaista liikennesuunnittelua. Tämän diplomityön tarkoituksena on käydä läpi sellaiset kylmiin olosuhteisiin soveltuvat sähköajoneuvoteknologiat, joiden voidaan osaltaan katsoa vastaavan kestävän kehityksen asettamiin haasteisiin. Teknologioiden käyttöä käsitellään niin julkisten kuin yksityistenkin käyttäjäsegmenttien näkökulmasta. Ajoneuvokannan sähköistämistä julkisessa liikenteessä tarkastellaan bussiliikenteen näkökulmasta. Yksityistä sektoria koskettaa lähemmin työssä käsitelty tavarankuljetusajoneuvojen sähköistäminen. Työ ei käsittele raideliikennettä. Työ on tehty kirjallisuustutkimuksena, johon on kerätty materiaalia useista Internet-lähteistä sekä tieteellisistä artikkeleista ja kirjoista. Tutkimusta tukevat myös kaksi haastattelua, joista ilmenee Helsingin seudulla vallitsevia asenteita ajoneuvojen sähköistämistä kohtaan. Käytetyn lähdemateriaalin avulla on pyritty saavuttamaan mahdollisimman laaja tietämys eri sähköajoneuvoteknologioiden nykytilasta ja käytöstä sekä niitä kohtaan osoitetusta mielenkiinnosta.</p> <p>Merkittävimmät työssä käsiteltävät sähköajoneuvoteknologiat ovat johdinbusseja sekä akku- ja polttokennotoimiset ajoneuvoteknologiat. Näitä teknologioita on verrattu työssä monipuolisesti. Nykyään paljon puhuttavan kestävän kehityksen näkökulmasta sähköajoneuvoteknologioiden mielekkyyteen vaikuttaa merkittävästi sähkön- ja vedyn tuotannon päästöprofiili. Sähköajoneuvojen houkuttelevuutta voidaan parantaa suosimalla matalapäästöisiä energiantuotantomuotoja. Diplomityössä selviää, ettei pelkän nykyisen akkuteknologian avulla vielä kyetä bussiliikenteen taloudellisesti kannattavaan sähköistämiseen. Polttokennojen lailla ajoneuvojen akut ovat vielä erittäin kalliita ja teknisesti kehittymättömiä. Akkuja voidaan kuitenkin käyttää järkevin perustein ajoneuvojen jarruenergian talteenottoon sekä pidentämään ajoneuvojen toimintasädetä. Tällä hetkellä soveltuvin sähköajoneuvo bussiliikenteeseen näyttäisi olevan johdinauto, joka on käsitellyistä vaihtoehdoista halvin ja ennen kaikkea pitkäikäisin. Johdinautoja on myös käytetty menestyksekkäästi kylmissä olosuhteissa. Tavarankuljetusliikenteen saralla pelkkien akkujen käyttöä ajoneuvojen energianlähteenä tullaan edistämään voimakkaammin. Jatkotutkimuksissa olisi suotavaa tutkia työssä käsiteltyjen teknologioiden yhdistelmiä käyttökelpoisimpien sähköajoneuvojen löytymiseksi.</p>	
Avainsanat: akku, energiavarasto, johdinauto, ladattava hybridi-ajoneuvo, polttokenno, sähköajoneuvo, sähköbussi	

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<p>Den finska trafikplaneringen har formulerat ambitiösa mål för att styra in utvecklingen mot mera hållbara fordonstekniker. Detta diplomarbete presenterar de mest användbara elfordonsteknologierna. De tekniker som diskuteras är lämpliga för kallare klimat och bidrar till hållbar utveckling. Diplomarbetet behandlar både de offentliga och privata trafiksektorerna. Elektrifieringen av offentliga fordon granskas genom den offentliga busstrafiken, medan privata fordon analyseras genom varutransporttrafiken. Järnvägstrafiken behandlas inte i detta diplomarbete. Litteraturen för undersökningen baserar sig på många Internetkällor, vetenskapliga artiklar och böcker. Därtill utfördes två intervjuer för att få information om attityder till elektrifieringen av fordon i den finska huvudstadsregionen. Utgående från det använda materialet presenterar detta diplomarbete många tidigare erfarenheter och uppdaterad information om elfordonsindustrin – d.v.s. utbredning, vanliga användningsändamål och intresse för elfordon.</p> <p>De signifikanta teknologier som bör beaktas vid elektrifieringen av fordon är trådbussar och olika fordon som använder batteri- eller bränslecellteknologier. En jämförelse mellan de här grundteknologierna är inkluderad i detta arbete. Hur hållbara de olika teknikerna miljömässigt är beror i hög grad på hur man producerar el och väte. För att producera mera genomförbara alternativ av elfordon för buss- och transporttrafiken, måste man först och främst främja lågmissionsteknologier inom el- och väteindustrin. Av detta diplomarbete framgår att elmatningen i elbussar inte kan lyckas med bara fordonsbatterier utan att dessa måste kompletteras med andra teknologier. Både fordonsbatterier och bränslekällor bör utvecklas för att möjliggöra lägre marknadspriser och bättre konkurrenskraft. Batterier kan trots allt utnyttjas till att återvinna bromsenergi samt som räckviddsförlängare eller extra energikälla. För närvarande verkar trådbussen vara det mest användbara alternativet för elektrifiering av busstrafiken. Trådbussar är billiga och har en mycket lång teknisk livslängd. De har även använts i kalla klimat på ett framgångsrikt sätt. Inom varutransporter kommer rena batteribilar att befordras kraftigare. För att finna de mest användbara och praktiska elfordonsteknikerna, rekommenderas det att kommande undersökningar ska granska möjligheter till kombinationer av olika fordonsteknologier.</p>	
<p>Nyckelord: batteri, bränslecell, elbuss, elfordon, energireserv, laddhybridbil, trådbuss</p>	

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Abbreviations and terms

AC	Alternating Current
APU	Auxiliary Power Unit
AUD	Australian Dollar
BEB	Battery-Electric Bus
BEV	Battery-Electric Vehicle
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
CUTE	Clean Urban Transport for Europe
DC	Direct Current
DGE	Diesel Gallon Equivalent
DMFC	Direct Methanol Fuel Cell
ECTOS	Ecological City TranspOrt System
EEV	Enhanced Environmentally friendly Vehicle
ELCIDIS	ELectric vehicles in CItY DIStribution
ESS	Energy Storage System
EU	European Union
EUR	Euro
EV	Electric Vehicle
-FC	-Fuel Cell
FCB	Fuel Cell Bus
FCHV	Fuel Cell Hybrid Vehicle
FCV	Fuel Cell Vehicle
FTA	Federal Transit Administration
HC	Hydrocarbon
HESB	Hybrid Electric School Bus
HEV	Hybrid Electric Vehicle
HSL	Helsinki Regional Transport Authority
HSY	Helsinki Region Environmental Services Authority
H ₂	Hydrogen
ICE	Internal Combustion Engine
IFEU	Institute for Energy and Environmental Research
LCO	Lithium-Cobalt Oxide
LEJ	Lithium Energy Japan
LFP or LiFePO ₄	Lithium Iron Phosphate

Li-ion	Lithium-ion
LMO	Lithium-manganese spinel
LTO	Lithium Titanate
NCA	Lithium-nickel-Cobalt-Aluminium
NiCd	Nickel Cadmium
Ni-MH	Nickel-Metal Hydride
NMC	lithium-Nickel-Manganese-Cobalt
NO _x	Mono-nitrogen oxides (<i>nitric oxide and nitrogen dioxide</i>)
OEM	Original Equipment Manufacturer
PAFC	Phosphoric Acid Fuel Cell
PEM	Polymer Electrolyte Membrane/Proton Exchange Membrane
PHEV	Plug-in Hybrid Electric Vehicle
PM	Particulate Matter
RMFC	Reformed Methanol Fuel Cell
SEV	Smith Electric Vehicles
STEP	Sustainable Transport Energy Project
UITP	International Association of Public Transport
USD	United States Dollar
V2G	Vehicle-to-Grid
tank-to-wheel	The efficiency pathway of a certain fuel or electricity from the tank of a vehicle to propulsive energy
well-to-tank	The efficiency pathway of a certain fuel or electricity from the production to the tank of a vehicle
well-to-wheel	The efficiency pathway of a certain fuel or electricity from the production to propulsive energy

Units

<i>A</i>	ampere
<i>dB (A)</i>	A-weighted desibel
<i>g</i>	gramme
<i>kg</i>	kilogramme
<i>km</i>	kilometre
<i>kWh</i>	kilowatt-hour
<i>kWh_{eq}</i>	kilowatt-hour equivalent
<i>mm</i>	millimetre
<i>V</i>	volt
<i>W</i>	watt
<i>Wh</i>	watt-hour
€	Euro

1 Introduction

1.1 General

Concerns about the sustainability and adequacy of energy have started a continuous process of change. Especially, in the industrialised world, people are now trying to find solutions for improved energy efficiency and cleaner living environments. Under the pressure of global warming, governments and international organisations have assessed wide-ranging measures, methods and restrictions for reducing emissions.

Road traffic releases a great amount of harmful emissions. While traffic flows are constantly growing, passenger and delivery transport require implementation of novel, innovative solutions in order to have control of traffic-based emissions. Presently, bus and delivery vehicle fleets mainly consist of vehicles relying on conventional fuels. Despite the improving engine technologies, the need for alternative fuels and electrification of vehicles is widely recognised. The electrification of vehicles combined with responsible production of electricity form a promising combination for making healthier cityscapes possible.

Electric vehicles (EVs) have been used in Finland before. Decades ago, the cities of Helsinki and Tampere still ran trolley buses as a part of public transport. However, since then, conventional vehicle types (e.g., diesel vehicles) have provided a more viable, economical choice of transport. Trying to reduce the amount of generated emissions and exhaust gases, several Finnish cities and companies are now striving for sustainability. Traffic poses one of the main sustainability challenges and is certainly taken into account in the national policies.

1.2 Aim and scope of the study

This thesis discusses the potential solutions for vehicle electrification considering both buses and goods delivery, focusing on sustainable implementations best suitable for the Finnish traffic conditions. The thesis does not cover rail traffic or any hybrid-electric vehicle (HEV) technologies. Some marginal electric vehicle technologies that do not seem to be capable of providing respectable enough transit solutions are either left out

of the study or discussed very briefly. The study emphasises electric vehicle solutions that enable an economically viable use of extensive vehicle fleets.

The work contributes to a larger project, also referred to as SIMBe (Smart Infrastructures for Electric Mobility in Built Environments). The purpose of SIMBe is to accelerate the introduction of sustainable, electric mobility in Finland. This study aims for presenting issues challenging the vehicle electrification in the Helsinki metropolitan area. One of the goals of this work is to reflect the attitudes of some local transport companies, which will help understand the level of openness to vehicle electrification in the Helsinki region.

The beginning of the thesis presents information about trolley buses, fuel cell buses (FCBs) and battery-electric buses (BEBs) in Chapters 2, 3 and 4, respectively. These chapters give a view of the basic technical features, related infrastructure, prices, as well as the current and prior use of the aforementioned vehicle technologies. Also environmental issues – e.g., generated emissions and exhausts – are covered in brief. Vehicle technology-specific information is given when appropriate. For instance, characteristics of the hydrogen fuel cell and vehicle battery technologies are addressed in Chapters 3 and 4, respectively. This information is generally applicable to all vehicles (i.e., not only buses) utilising fuel cells or batteries for propulsion. Chapter 5 condenses the knowledge of the three prior chapters adding some supplementary, supportive information. In Chapter 6, the attitudes towards electrification and possible vehicle technologies for regional bus transport are evaluated through an interview with a transport authority operating in the Helsinki metropolitan area. Chapter 7 discusses the role of the delivery of goods in the introduction of electric vehicles. Moreover, the chapter gives a brief view of the efforts made for vehicle electrification in the Finnish mail delivery through a quick interview with a Finnish postal transport company. Finally, Chapter 8 concludes the thesis by presenting a few essential points about the feasibility of different electric vehicle technologies in the Finnish bus and delivery traffic.

1.3 References and methods of research

The electric vehicle technologies discussed in the thesis were chosen based on information gathered from various Internet sources, scientific articles and books. The emphasis is on the public Internet sources since there is little information available in scientific literature about the research subject. Additionally, two major transport companies in the Helsinki metropolitan area were interviewed. The interviews contribute to the study by providing information about the current use of different vehicle technologies, as well as showing the attitudes towards alternative vehicle technologies in the Helsinki region.

Thus, the feasibility of the discussed electric vehicle technologies is partly addressed through these interviews.

The thesis compares several quantitative and qualitative parameters of the considered electric vehicle technologies with each other. Quantitatively, the technologies are mainly analysed in terms of efficiency, energy consumption and emissions, as well as vehicle range, expected lifetime and occurred costs. Moreover, the need for additional infrastructure and maintenance is examined. The study occasionally uses terms ‘tank-to-wheel’, ‘well-to-tank’ and ‘well-to-wheel’ to help define the efficiencies of the vehicles and the production of electricity or hydrogen fuel (see Abbreviations and terms). The qualitative comparison takes into account factors like passenger comfort and infrastructure-related aesthetics. The results and conclusions are mainly presented from a transport operator or passenger point of view.

2 Trolley buses

2.1 Background of the trolley bus – future prospects

The past experiences with trolley buses have been versatile. The first attempts using a trolley bus – that one referred to as *Elektromote* – were conducted in 1882 without any appreciable success. Later in the beginning of the twentieth century, Lombart-Gerin managed to build probably the first working trolley bus line for the Paris Exhibition of 1900. [1] Trolley buses were first introduced in Finland in the late 1940s. Helsinki started trolley bus traffic on 5th February 1949 [2]. Another town to begin trolley bus traffic in Finland was Tampere. Compared with diesel buses, trolley buses offered more effective driving with better acceleration and higher travel speed. The longevity and economic efficiency also favoured these vehicles. In Helsinki, the largest trolley bus line comprised 26 operating trolley buses. Figure 1 presents a trolley bus of that time with the included infrastructure in Helsinki. [3]



Figure 1: A trolley bus on line #14 in Helsinki. Photo by Suomen Raitioseura ry. [2]

However, in Helsinki, diesel buses began their rally in the 1960s, as they started to substitute trolley buses. Diesel buses developed quickly and displaced the interest in electric mobility. Diesel now offered better operating characteristics, and as they were seemingly more flexible than trolley buses, they began to increase in popularity. Generally, environmental factors were not driving technical development. The trolley bus network did not expand in Finland. In contrast to the Finnish traffic planning, there were other European countries promoting the use of trolley buses. For instance, in Switzerland, diesel buses were left as poor challengers. Switzerland had plenty of electricity produced by hydroelectric power plants, and while the Swiss typically had appreciated clean, peaceful city surroundings, trolley buses were an advantageous, natural addition to their traffic planning. Until now, along with some East European countries, Switzerland has kept its trolley bus traffic active. [3]

Albeit the diesel bus was forcefully gaining momentum, the city of Helsinki did not immediately dispense with all the trolley buses. As late as in 1973, Helsinki tried three new Russian trolley buses. The results were not admirable. One year after that, it was decided to close down the trolley bus traffic. Tampere proceeded the same way and quit the operation two years after Helsinki had come to its decision. Some efforts were made to give rebirth to trolley bus traffic after the closures, but these efforts simply came short of their objective, and trolley buses were continuously seen as a too expensive option. In Helsinki, it was estimated that the trolley bus system – compared with a similar traffic arrangement implemented with diesel buses – would incur approximately 15 percent higher costs [2]. In 1985, the city government confirmed the decision concerning the dismantling of the trolley bus line. Yet, the city government stated that the option of trolley buses would be reconsidered in the future, if the technical or economic situation would notably change. [3]

Since 1970, the interest towards trolley buses has been increasing on an international level. There has been more emphasis on environmental thinking, which has favoured trolley buses in respect to their low noise levels and minimal pollution generation. One has financially supported public transport, and more emphasis has been put on societal thinking. Tax subsidies and other economic aid have been allocated for trolley bus systems [2]. This has helped transport operators boost their environmental attitudes and awareness. Positive attitudes towards increasing the use of trolley buses have strengthened along with the pursuit of reduced oil dependency. [4]

At present, approximately 400 trolley bus systems in various cities around the world are active. About 300 of these are located in post-Soviet states. Western Europe comprises around 50 systems. Nordic countries have trolley buses in Bergen, Norway and in Landskrona, Sweden. Figure 2 illustrates an active trolley bus on the line in Landskrona.

The closest trolley bus system from a Finnish perspective can be found in Tallinn, Estonia. [2]



Figure 2: A trolley bus in service in Landskrona, Sweden [5]

Cities that already run trolley buses are now rehabilitating their fleets. During the last decade, Athens in Greece, Arnhem in Holland and Sarajevo in Bosnia and Herzegovina among other European cities have expanded their existing trolley bus systems. Old vehicles have been upgraded. Trolley buses have also been used in some Asian and Latin American countries. Besides the renovation of old systems, several countries – e.g., Canada, China, England, Belarus, Czechoslovakia, France, Italy, Russia, Spain, Switzerland and the United States – have been introducing new, advanced trolley bus models in recent years. [2] [4] [6]

Now, some 25 years after the Helsinki city government's decision to close down the trolley bus traffic, the concept of trolley bus evokes serious governmental interest again. Introductions of new trolley bus systems in other countries, as well as strict domestic and international environmental goals have had strong influence on the Finnish traffic planning. In 2009, the planning unit of Helsinki city transport published a feasibility study on possible trolley bus systems in Helsinki. [3]

2.2 *Basic characteristics of trolley buses*

Trolley buses have some unique features. The steering system and vehicle body of a trolley bus are practically similar to those of normal diesel buses. Though, there have been differing vehicle body concepts on the market recently [3]. The newest models are very similar to modern trams [2]. In contrast to diesel buses, trolley buses are characterised by electric propulsion and attachment to overhead wires. This feature – trolley poles – makes them similar to rail traffic modes. The route of a trolley bus is fixed because of the stationary essence of the overhead wires that give the vehicle its electric power. Trolley buses create more powerful traction than diesel buses. They accelerate smoothly but quickly; excellent torque properties of electric motors help trolley buses climb up steep hills. [4]

At present, it is very frequently seen that trolley buses carry particular auxiliary power units (APU) which keep them in motion, whenever the overhead wires are not available. APUs increase the reliability of trolley buses as a traffic mode. With the help of an APU, a trolley bus can pass obstacles in traffic, as well as drive differing routes depending on the traffic demands. Trolley buses are thus not so sensitive to traffic disturbances as trams or other fixed traffic modes with rails. [3]

Typically, trolley bus APUs are diesel internal combustion engines (ICE). The most advanced solutions use chemical batteries and capacitors as an on-board energy storage system (ESS). Diesel ICEs range normally from a 50-kW booster motor to a 200-kW engine. With a small booster it is possible to move small distances with low speed. This makes it possible for trolley buses to avoid stops caused by maintenance work or other disturbances. The booster also enables moving on depots, if no overhead network is available. A larger engine can be a real option for electric propulsion supplied by the overhead network. Vehicles with two concurrent propulsion systems which can be run at similar power levels are commonly referred to as dual-mode vehicles. The use of a battery and capacitor assisted ESS induces greater expenses than a correspondent diesel ICE. However, in the most advanced systems, super capacitors of a greater capacity can be charged on bus stops, making it possible for the vehicle to have no wire contact en route. Naturally, such vehicles would not be described as trolley buses, more likely they would be classified as super capacitor buses. [3]

Trolley buses are mostly equipped with alternating current (AC) motors. Earlier models often used direct current (DC). However, AC motors are lighter, assembled of less expensive parts, and their speed regulation is better. Electric traction motors can be used as effective, advantageous electric brakes. Compared to average mechanical brakes, electric brakes significantly reduce the wear of mechanical braking components and tyres. The electric braking energy can either be dissipated in the vehicle's resistors, when the

vehicle decelerates, or used to charge possible batteries and capacitors of the vehicle, or simply fed back into the overhead network. Conducting the braking energy back into the system is commonly referred to as regeneration or recuperation of electric energy. [6]
[7]

Trolley buses carry trolley poles that collect the current used for propulsion from the overhead wires. Poles, shown in Figure 3, are usually about 5 metres in length, depending on the vehicle type and traffic arrangements. Modern trolley poles feature low mass and high stiffness properties which reduce the possibility of detaching from the wire or ‘dewiring’ [8]. They are lifted and lowered pneumatically, when the vehicle is stopped. Lifting of the poles usually happens manually and lowering either manually or automatically. In some cases, overhead wires are equipped with funnels (Figure 4) that direct the pole to the right place – onto the lower surface of the overhead wires – during the lifting process. This necessitates the vehicle to be in an exact spot for the lift. Poles do not easily fall away from the wires in a sideways movement, which helps the trolley bus avoid obstacles in traffic. [3]

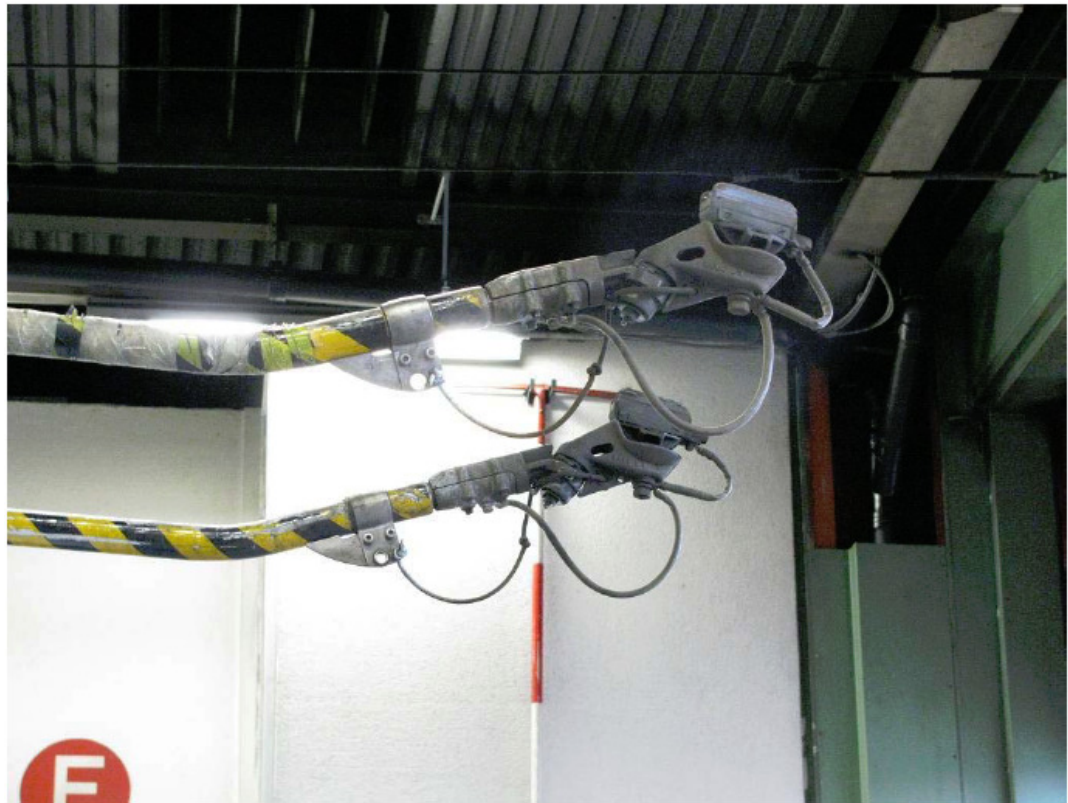


Figure 3: Heads of trolley poles [3]



Figure 4: Funnels on overhead wires [3]

Trolley buses hold greater transport capacity than normal buses, but lag behind trams in contrast. Trolley buses are generally articulated with one or two articulations and are in some cases up to 24 metres long. But even the largest trolley buses hold less transport capacity than trams because of the size difference. [3]

All new European trolley buses have low floors or at least a kneeling function, which makes it easier for people to enter and leave the vehicle. Low floors and easy access to the vehicle creates customer satisfaction and reduces costs generated by the unnecessary waiting time, when people are boarding or alighting. Noteworthy is that also electric traction motors contribute to the benefits achieved by low floors. Trolley buses usually have a single traction motor connected straight to the drive shaft without any gearbox or clutch [7]. In newer models, motors are often implemented as so called wheel hub drives which are mounted next to each drive wheel into the wheel hub. Trolley buses with wheel hub drives do not need long drive shafts, so the whole floor of the vehicle can be made flat without any angles or elevations. This eliminates the idea of utilising old buses with drive shafts in trolley bus conversion. Wheel hubs drives enable implementing innovative structures in trolley buses. Seats, for example, can hang from strengthened walls to free the even floor space for easy cleaning. [6]

Modern trolley buses have various similarities. A closer look at Škoda's web pages reveals that nearly all new or newish trolley bus models are equipped with low-floor features. Additionally, they hold a full air conditioning and audio-visual passenger information system. Almost all modern trolley buses have a kneeling function to increase passenger comfort. The trolley bus model in Landskrona, Sweden has NiMH batteries for autonomous running. Every Škoda trolley bus model also has recuperation functionality for braking energy. [9]

The newest trolley bus model of Škoda, the ŠKODA 24 Tr IRISBUS, has an asynchronous traction motor of 210 kW. It holds 28 seats and 58 places for standing passengers. The vehicle has a modular design, which allows the buying customer to decide the details implemented in the vehicle. Uncharacteristically, the ŠKODA 24 Tr IRISBUS has two APUs – a diesel engine and traction batteries alike. [9]

2.3 *Infrastructure on roads and trolley bus depots*

Even though trolley buses use overhead wires to function, they cannot use the same wires with trams. An electrotechnical reason limits the use of shared wires. Trams have a single electric supply wire. They use rails as a return current path, whereas trolley buses must have two overhead wires, one for electric supply and another for return current. [3]

An essential part of the trolley bus network is the power supply through electrical substations. To monitor the return current in an appropriate way, and for the sake of electrical safety, line outputs from substations must be made separately for trolley buses and trams. Moreover, the adequacy of the substations must be examined. In Helsinki, new substations are not necessarily needed for new trolley buses, if the overall power requirement of the utilised vehicles stays under the supply capacity of the substations. Furthermore, the existing substations are most probably dimensioned considering the energy consumption of trams, which is higher than the consumption of trolley buses. This supports the idea of trolley buses utilising already existing substations. When needed, stations can be strengthened with super capacitors to support the voltage level. However, it would be necessary to build new substations in areas outside the electric supply for trams. Trolley buses typically require one substation for every three line kilometres. [3]

Existing systems for trolley bus power supply range from 600 to 1,000 V DC. The most probable option for Helsinki city traffic would be 750 V DC. The Helsinki city has planned to reshape the power supply system for trams. The intention is to switch from 600 to 750 V DC. Using a common voltage level would enable the use of identical

power supplies for both trams and trolley buses. Using higher voltage level also makes it possible to have lighter, cheaper overhead wires because of reduced supply current. Added to this, lighter wires are visually less disturbing. [3] [8]

A couple of different types of cables and wires are required in a trolley bus network. The power supply for the overhead wire network consists of cables from tens to a few hundred metres long. Direct current produces an electromagnetic field around the cable. Electromagnetic fields are phenomena that are intensively studied for health reasons. Nevertheless, electromagnetic fields generated by overhead wires for trolley buses are milder than the fields generated by tram lines. The wires for supply current and return current partly compensate each other. Overhead wires typically hang 5.5 metres above the street surface. Wires situated very high up weaken the possibility of sideways motion. Normally, a trolley bus can move about 4 metres to each side. Overhead wires require supporting structures that are typically used for all the wires simultaneously. A two-way trolley bus lane consists of four copper wires which can be supported with the same supporting structures. Trolley buses using partly common driving lanes need 'points' or 'switches' in the overhead line structure in order to direct trolley poles to the right place. There are mechanical and electrical points. The operation of electrical points can be controlled. Mechanical points only have a single functionality. Modern points and well-functioning overhead wires enable trolley buses to operate without having to decelerate [8]. An overhead wire network also includes several wire crossing mechanisms, electrical separators, an electrical feeding point infrastructure and supports for the wiring. [3]

Trolley bus depots generally require an overhead wire network enabling easy movement of vehicles. Though, it is possible to avoid heavy wiring systems in the depots by deploying trolley buses with APUs. Depots must have equipment for live working and other maintenance work. For live working, it is necessary to have special hoist frames, because usually all the electrical equipment is on the roof of the vehicle. In the depot, trolley buses should be covered by at least some kind of roof. Preferably, they should stay in a space equipped with both a roof and walls. Depots must have enough room for washing the trolley bus chassis as well. In Helsinki, the main concern over having trolley buses in the depots is the lack of space or the difficulty of utilising the space in an effective manner. Special arrangements in maintenance rooms and depot interiors should be considered on all existing depots, if trolley buses were introduced in Helsinki city traffic. The use of trolley buses would also affect other traffic – the placement, maintenance and driving schedules of other vehicles etc. [3]

Trolley bus systems commonly require street level rebuilding. In addition to the characteristic supporting structures and overhead line networks, the use of trolley buses may involve arrangements in lane structures. Occasionally, routes with only one lane are

built to avoid surplus costs. In that case, the lane should work in both ways without creating excessive congestion. A typical system involves two lanes, one for each direction, enabling simultaneous two-way traffic. [3]

2.4 Costs of trolley bus investment, maintenance and infrastructure

Acquisition costs of trolley buses have reduced during the twenty-first century. Reasons behind this originate from increased demand. Trolley bus production has become more efficient and competition in the market has gained momentum. In recent years, the average price of a trolley bus offered by most known competitors has varied between EUR 450,000 and EUR 750,000 (2009). An illustrative point of comparison here would be the price of a diesel bus that is around EUR 250,000 – 350,000 (2009). Certain technical characteristics affect the price in both cases. Slightly booming trolley bus markets have generated a secondary market where fully operational vehicles can be bought for under half price. [3]

An investment in trolley buses necessitates commitment to it. Initial investments and renewal rates of specific technology-related equipment are clearly higher than those of average diesel buses. Also the rehabilitation of a trolley bus fleet induces greater expenditures. [3]

On the contrary, the operating life of a trolley bus is significantly higher. It can reach between 16 – 20 years, whereas diesel buses must be substituted every 14 – 15 years. The motor of a diesel vehicle creates vibration that fatigues the body of the vehicle. Therefore, diesel bus fleets must be substituted more often. [3]

The costs of a trolley bus infrastructure consist of different variables. This is shown in the Helsinki feasibility study on trolley bus systems. Basically, there are two main cost components. A direct current substation, including its shed, costs around EUR 500,000. Overhead wire network for a two-way trolley bus lane incurs expenditures of circa EUR 300,000 per kilometre including the supporting structures. Additionally, electrical points for choosing the route cost EUR 55,000 each. Overhead wires typically cross each other on the streets. Mechanisms for these crossings are usually worth tens of thousands of Euros. Poles for supporting the wires cost a few thousand Euros and remote-controlled electrical separators around EUR 15,000 per piece. An electrical feeding point without a separator is worth EUR 6,500 including its installation. The aforementioned prices are from 2009. [3]

According to the pronouncement of a Swedish local traffic company, AB Storstockholms Lokaltrafik, the overall surplus cost of a trolley bus system compared with an average bus system would be circa 6 – 17 percent. This estimation takes into account expenditures incurred from trolley bus fleet investment, infrastructure, insurance, energy used and maintenance. The operating life of the trolley bus fleet is also considered. The estimation is based on UITP (International Association of Public Transport) studies. In some cases, the system implemented could be much more expensive depending on the expensiveness of the overhead wires, related infrastructure and the size of the system. AB Storstockholms Lokaltrafik names the small-size trolley bus system of Landskrona, Sweden, to give an example of a system much more expensive than an average trolley bus system. [10]

2.5 *Impacts on environment*

Trolley buses carry passengers rather efficiently. Compared to diesel vehicles, trolley buses provide a few clear advantages. In general, it is seen that every power plant holds better efficiency producing electricity than the efficiency of a combustion engine. The Helsinki feasibility study on trolley bus systems suggests that trolley buses consume 2.5 kWh of energy per kilometre. This value considers the total amount of energy used by a trolley bus with one articulation. The feasibility study brings out an aspect regarding the location of trolley bus emissions. Nitrogen oxides (NO_x) and particulate matter (PM) emissions of diesel buses endanger the people next to the vehicle, whereas the comparable emissions of trolley buses are concentrated close to the power plant, where the electricity is produced. [3]

Environmental impacts of a rubber tyred trolley bus remain low. A trolley bus does not generate exhausts at all. The only harm to the environment occurs from the detrimental dust that comes off the tyres of a moving trolley bus. Consequently, trolley buses do not need any exhaust pipes. In auxiliary power unit application cases, trolley buses may also produce exhausts, but only when working on the APU. The noiselessness of electric drives also involves added value for the city environment. Occasionally, the overhead wire networks can be visually disturbing, while especially the junctions of several wires and switches are dominating the street view. In order to mitigate the visual inconvenience, trolley bus systems are increasingly equipped with overhead wires of stainless steel [6]. [4]

3 Fuel cell buses

3.1 A brief history and development of fuel cells

The technology for a fuel cell was first discovered in 1839, when William Grove used reversed water electrolysis to generate electricity from hydrogen and oxygen. With the help of fuel and an oxidant, a fuel cell converts chemical energy into electric energy in a continuous manner. A fuel cell resembles an engine with its continuous fuel consumption, and batteries because of their electrochemical processes. [11]

The first practical application of a fuel cell provided the Gemini and Apollo space programmes a means to generate electric power and drinking water. Water and heat are the only by-products generated in the operation of a fuel cell, when pure hydrogen (H_2) is used as fuel [12]. These space programmes utilised polymer electrolyte membrane fuel cell or proton exchange membrane fuel cell (PEMFC) technology – invented by General Electric in the 1960s. However, the PEMFC technology was overly expensive because of the platinum used as a catalyst on the electrodes of the fuel cell. The use of PEMFCs, which later became extremely important for transport sector, was restricted to space applications. [11] [13]

In the early 1980s, a company referred to as Ballard Power Systems Inc. began to redevelop the earlier abandoned PEM fuel cell of General Electric. The company pursued for cheaper materials and methods to produce PEM fuel cells. [13] The late 1980s and early 1990s were a significant period for fuel cells in transport. Conventional diesel-powered transit buses could not compete with hydrogen and other alternative fuels when the interest in reducing emissions saw its rise. Proofing the reliability of fuel cell buses (FCBs) under various circumstances as a part of public transport formed the main target for the industry. Reliability issues are confronted presently as well. However, after various fuel cell transit bus demonstrations, it is now truly recognised that fuel cell technologies can compete with conventional propulsion technologies. [14]

3.2 *PEMFC technology for transport*

The future of modern fuel cells in the transport sector looks optimistic. In general, fuel cells are extremely attractive because of their capability to emit zero or very low levels of emissions. Fuel cells are also more efficient than average ICEs (e.g., PEM fuel cells typically provide efficiencies between 40 and 60 percent) [15]. The high efficiency is mainly based on the electrochemical characteristics of the fuel cell power generation process. [11]

PEM fuel cells provide end user applications in three main categories. Transport applications include buses, light-duty and specific niche applications. The two other categories involve stationary use of PEMFCs and portable PEMFC-powered devices. The proportional use of PEMFCs by application area is shown in Figure 5. The transport sector holds around 15 percent of the total end use. Although PEM fuel cells are mainly used in not vehicle-related applications and buses embrace only a fraction of the total end use, PEMFCs are recognised as the most applicable fuel cell type for the automotive industry, including buses [16]. [15]

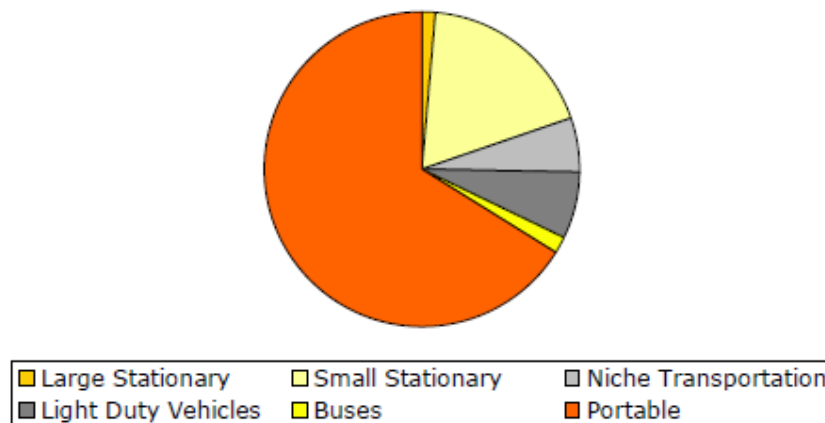


Figure 5: Proportions of globally installed PEMFC-powered applications [15]

A simple description is enough to show the basic functionality of a PEM fuel cell. A thin, permeable polymeric membrane works as the electrolyte in the fuel cell. On both sides of the membrane, platinum-based electrodes catalyse the electric power-creating reaction. In the basic process, hydrogen molecules are exposed to the anode, where they split into hydrogen ions (protons) and electrons. Protons are capable of permeating the polymeric membrane, whereas the electrons – the electric current – are led to an external circuit. In vehicular applications, the current is mainly fed to propulsive electric motors. Oxygen from the air and electrons from the external circuit combine with the hydrogen

ions at the cathode to form heat and water. An illustration of the basic fuel cell process can be found in Figure 6. [15] [17]

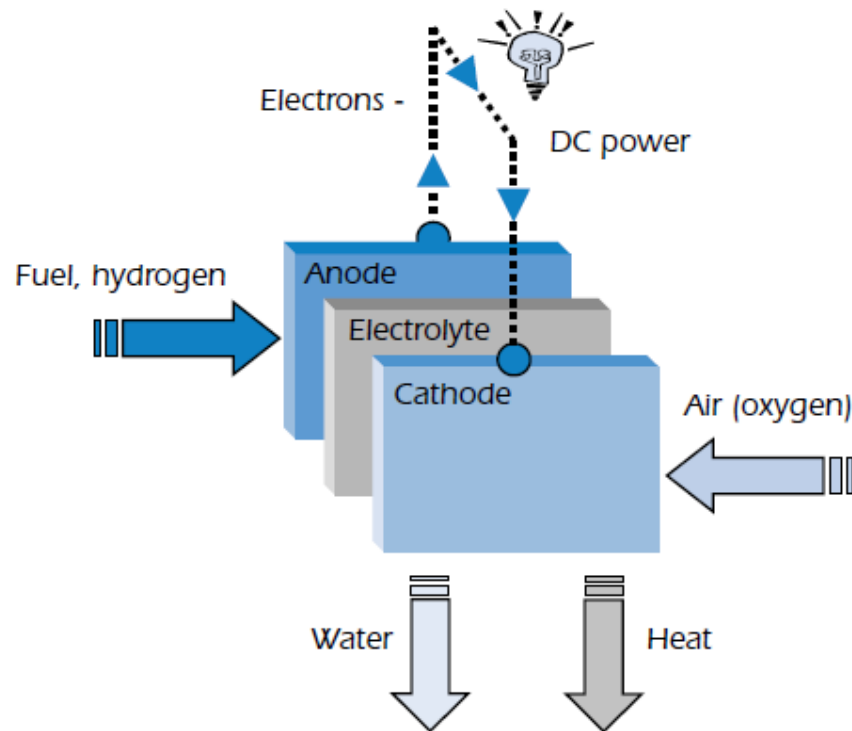


Figure 6: The concept of a fuel cell [18]

From various fuel cell types, the PEMFC has proven to be the favourite choice of modern transport. PEMFCs have the advantage of being both lightweight and compact. Their power-to-weight-ratios are often high, which is counted as an advantage in automotive usage [18]. The typical electric power attained by a PEM fuel cell is up to 250 kW. The operating temperatures of PEMFCs are low, typically approximating 60 – 80 °C [19]. This makes a quick start-up of the fuel cell vehicle possible. Additionally, a solid electrolyte membrane enables the use of a less expensive sealing for gases produced in the anode and cathode. Compared with some other electrolyte materials, the polymeric membrane also avoids corrosion better, which extends the life expectancy of the fuel cell. [15]

A few technical difficulties with PEM fuel cells occur from the characteristics of the fuel cell type. The most commonly used membrane type for PEMFCs is Nafion by DuPont. This membrane type must be saturated with water to achieve appropriate operating conditions. Local drying of the membrane exposes it to degradation. Another issue concerns the operating temperature. The trade-off with the typically low operating temperature of PEMFC is the lack of excess heat from the fuel cell. The amount of heat pro-

duced is often inadequate for cogeneration. Thus, one must find out other methods to arrange the heating of the interior in PEMFC-powered vehicles. The heating issue particularly concerns countries with cold, harsh climates, such as Finland. [15] [20]

As an alternative to PEMFCs that use pure hydrogen as fuel, various automotive manufacturers have considered fuel cells that utilise methanol. For instance, reformed methanol fuel cells (RMFCs) and direct methanol fuel cells (DMFCs) use methanol as a carrier for hydrogen. An RMFC has an auxiliary reformer for converting methanol to hydrogen and other substances. Methanol is relatively easy to transport and could solve several problems related to the hydrogen storage, transport and distribution. However, these fuel cell types generate carbon dioxide (CO₂) emissions, whereas PEMFCs provide operation totally free of CO₂. [21] [22]

3.3 Use of fuel cells in modern public transport – a look at the available technology

Hydrogen has been utilised in various public transport projects since the early 1990s. Hydrogen fuel cell-powered vehicles and hydrogen-fuelled ICEs, as well as other fuelling and related technologies have been promoted widely worldwide. Demonstration projects in the United States, Europe, China, Japan and Australia have introduced a diverse range of new technologies into the markets. Only during the past decade, more than 20 cities have utilised hydrogen-powered buses in their bus repertoire. [23]

Assessing the durability of hydrogen fuel cell buses has interested several parties, and therefore, various demonstrations have been used to control the impacts of long duty cycles on the vehicles. [23] In order to increase competitiveness in the transport sector, the fuel cell industry has had various practical objectives: reducing the size, as well as increasing the power density of fuel cell stacks; reducing the overall weight of fuel cell systems including electric propulsion; developing a hydrogen infrastructure to efficiently service vehicular use; optimising electric motors and control systems; proofing electric propulsion systems safe for transit vehicles, and capable of operating dependably under extreme weather conditions. Diverse fuel cell bus demonstration projects implemented around the world are presented in Table 1. [14]

Table 1: An overview of the fuel cell bus demonstrations worldwide [14] [24] [25]

Project Dates	Status	Project	Location	Description
1994-1995	Complete	Federal Transit Administration (FTA)/Georgetown	Various	Three 30-ft FCBs operating on methanol using 100 kW phosphoric acid fuel cell (PAFC) stacks from Fuji
1998	Complete	FTA/Georgetown	Various	40-ft FCB operating on methanol using 100 kW PAFC from UTC Power
1998-2000	Complete	Ballard Phase III	Chicago, IL, and Vancouver, Canada	Test program with six 40-ft FCBs using 205 kW proton exchange membrane fuel cell stacks from Ballard
2000-2001	Complete	Ballard Phase IV	Thousand Palms, CA	Test bus using 200 kW PEM fuel cell stack from Ballard
2000-	In Service	CityCell	Turin, Italy	One UTC Power 60 kW powerplant, hybrid bus, showcased in 2006 Winter Olympics
2000-2003	Complete	CityCell	Madrid, Spain	One UTC Power 60 kW powerplant, hybrid bus
2001	Development	FTA/Georgetown	Various	40-ft FCB operating on methanol using 100 kW PEM fuel cell stack from Ballard
2002-2002	Complete	ISE/UTC Power ThunderPower	Thousand Palms and Oakland, CA	ThunderPower 30-ft FCB using 60 kW PEM fuel cell stack from UTC Power, ISE hybrid system
2003-2006	Complete	CUTE, ECTOS, STEP	Europe, Iceland, and Australia	33 40-ft FCBs using Ballard PEM fuel cell stacks
2003-2006	In Service	Hino/Toyota FCB - JHFC	Japan	Eight 40-ft hybrid FCBs with Toyota PEM fuel cell stacks
2004-2007	In Service	VTA	San Jose, CA	Three 40-ft FCBs using Ballard fuel cell stacks
2004-2006	In Service	UNDP-GEF China	Beijing, China	Three 40-ft FCBs using Ballard PEM fuel cell stacks
2004-	In Service	SunLine	Thousand Palms, CA	One 40-ft FCB using UTC Power fuel cell stack, ISE hybrid system
2004-	In Service	Hickam AFB	Honolulu, HI	One battery dominant plug-in hybrid FCB with Hydrogenics PEM fuel cell and Enova hybrid system
2005-2007	In Service	AC Transit	Oakland, Ca	Three 40-ft FCBs using UTC Power fuel cell stacks, ISE hybrid system

2006-2009	In Service	HyFLEET CUTE	Europe, Iceland, China, and Australia	One-year extension of the demonstration of the Citaro/ Ballard FCBs and new demonstration of 14 hydrogen-fueled internal combustion engine buses (MAN)
2006	Complete	NRCan/Hydrogenics	Winnipeg, Canada	One 40-ft hybrid FCB using Hydrogenics PEM fuel cells
2006-	In Service	Van Hool	Delijn, Belgium	One 43-ft hybrid using UTC Power 120 kW fuel cell, to be leased later to other European transit agencies
2007-	In Service	UNDP-GEF Brazil	Sao Paulo, Brazil	Five hybrid FCBs using a Ballard fuel cell
2007-	In Service	CT Transit	Hartford, CT	One 40-ft hybrid FCB using UTC Power 120 kW fuel cell stacks, ISE hybrid system
2007-	In Service	University of Delaware	Newark, Delaware	One 22-ft, battery dominant plug-in hybrid FCB using a Ballard fuel cell and Ebus hybrid system
2007-	Planning	FTA NFCBP	Various locations in the United States	U.S. demonstration of FCBs to advance technology commercialization; competitive solicitation to award \$49 million over 4 years to selected projects
2007-	Development	Georgetown University	Washington, DC	Development and demo of a 30-ft bus with a 60-kW automotive-sized PEM fuel cell powered by an on-board methanol reformer
2007-	Development	CARB, City of Burbank	Burbank, CA	Development of a battery dominant, 35-ft, plug-in hybrid FCB with Hydrogenics fuel cell in a Mobile Energy Solutions bus
2007-2014	Development	BC Transit, New Flyer, ISE, Ballard	Whistler, Vancouver, BC Canada	Operation of 20 hybrid FCBs in British Columbia for the 2010 Olympics

In the European Union (EU), the project CUTE (Clean Urban Transport for Europe) promoted the use of fuel cell buses in public transport in 2003 – 2006. CUTE was the first programme to incorporate a significant number of simultaneously operating fuel cell buses, as the earlier programmes typically involved only a few buses. Altogether, 27 fuel cell buses were run on the streets of Amsterdam, Barcelona, Hamburg, London, Luxembourg, Madrid, Porto, Stockholm and Stuttgart. Buses were deployed either in regular traffic or on extra routes specifically designed for fuel cell buses within the project. A great amount of information on usability was obtained because of the extensive deployment of buses, as well as the various city environments and fuelling infrastructures. CUTE substantially improved public attitudes towards hydrogen and led the development of a more secure supply of energy in the EU. However, the CUTE pro-

gramme also showed that fuel cell and related technologies were not perfectly finalised and the operation of fuel cells should be improved through re-engineering. [24] [26]

An Icelandic project ECTOS (Ecological City TranspOrt System) aimed for demonstrating the status quo of the modern hydrogen technology in Iceland. ECTOS concentrated on studying socio-economic influences within changing the energy base of an urban society. [27] The project ECTOS deployed three fuel cell buses, starting in 2003. The project was based on a grant of EUR 3.8 million from the European Commission. The original ECTOS project was closed down in 2005 but run under another programme for a year afterwards. In total, ECTOS buses travelled nearly 90,000 kilometres using slightly over 17.3 tonnes of hydrogen. [23]

The STEP (Sustainable Transport Energy Project) project explored the use of alternative energies in transport in Perth, Australia. STEP was supported by the Australian government. [28] The flagship project for the STEP project, EcoBus fuel cell bus trial, lasted for two years from 2004 to 2006. EcoBus was a success and contributed to the STEP project by achieving great environmental savings. 300 tonnes of tailpipe carbon emissions were avoided, and over 320,000 passengers were carried during the trial. Altogether, the three buses used in the trial travelled 258,000 kilometres and consumed 46 tonnes of hydrogen as fuel. [29]

All three projects were continued under the global HyFLEET:CUTE programme that was established by the European Commission in January 2006 to follow the productive work of the former CUTE programme. The projects originally referred to as ECTOS and EcoBus were run an extra year between 2006 and 2007. The HyFLEET:CUTE project lasted till the autumn of 2009 and employed 33 fuel cell buses in nine cities around the world. The CUTE, ECTOS and STEP projects consumed 229 tonnes of hydrogen, while the HyFLEET:CUTE project had a consumption of 326 tonnes. On-site production of hydrogen in HyFLEET:CUTE reached 158 hydrogen tonnes. A majority of this hydrogen was produced with renewable energy. [23] [25]

Earlier fuel cell bus projects have encouraged transit agencies and other players in the field to proceed with the development. One illustrative example of the deployment of fuel cell buses comes from the United States. Transit operators AC Transit, Santa Clara VTA and SunLine Transit Agency in the United States collected valuable data – to assess costs, fuel consumption, reliability, performance and customer acceptance – from fuel cell buses from 2005 through 2007. The operators now run fuel cell buses partly on regular service routes. Some of the buses operate 16 hours per day throughout the whole week. Currently, more transit agencies are about to join the programme initially financed by a federal transit authority. [30] [31]

Some of the buses utilised in the latter programme were powered by UTC Power, a unit of United Technologies Corporation [24]. In January 2010, UTC Power reported that one of its latest generation PureMotion® Model 120 fuel cell power plants for hybrid-electric transit buses had surpassed 5,000 hours of operation in common transit service. Noteworthy is that the buses had only used the original fuel cell stacks with no cell replacements. PureMotion® Model 120 is based on PEMFC technology [32]. UTC Power Vice President (Transport) Ken Stewart highly appreciated the achievement and saw fuel cell stack durability as the key factor in commercialising fuel cell vehicles (FCVs) worldwide. Hydrogen Bus Alliance has set a target concerning commercial fuel cell stacks in buses. The purpose is to attain 20,000 operational hours by 2015 [33]. [31]

One of the newest PEMFCs for automotive usage is the hydrogen-powered FCvelocity™-HD6 fuel cell of the Canadian Ballard Power Systems Inc. The fuel cell, shown in Figure 7, is intended for buses and heavy duty vehicles. The two sizes – 75 kW and 150 kW – can supply voltage levels of 275 – 400 V DC and 550 – 800 V DC, respectively. FCvelocity™-HD6 provides a rated current of 300 A, and has a volume of 0.55 m³. Its operation temperature is around 63 °C. The protection against dust and moisture fulfils the requirements of enclosure class IP54. The bigger FCvelocity™-HD6 module weighs less than 400 kg when dry. The smaller one weighs approximately 50 kg less. The lifetime target for this particular PEMFC is up to 6,000 hours. [19] [34]



Figure 7: The FCvelocity™-HD6 fuel cell [34]

Ballard introduced a fleet of 20 fuel cell buses operating on FCvelocity™-HD6 technology for the Olympic and Paralympic Winter Games in Canada (2010). The fleet was integrated into the regular service of BC Transit – a local transport agency in Whistler, British Columbia. The BC Transit demonstration programme lasts until 2014 and evaluates costs, performance and service availability of the low-floor, 12-metre New Flyer buses with hybrid propulsion from ISE/Siemens and valence lithium phosphate batteries

for energy storage. The fuel cell system powers the buses with 150 kW. One of the intentions creating the bus was that it would resemble an average bus regarding the driving behaviour and appearance, and still provide a clean energy future through environmentally advantageous choice of transport. [35] [36] [37]

3.4 Technical characteristics of a Mercedes-Benz fuel-cell-Citaro

A natural approach for assessing the opportunities to utilise fuel cells in domestic vehicle fleets is to review technological applications promoted elsewhere. To assess the suitability of fuel cell buses for Finnish transport, it is useful to consider bus fleets deployed in countries with similar weather conditions. The buses used in the project ECTOS in Iceland are examined to get a view of the technology involved. They have had to operate under harsh circumstances and thus create extra value for the examination.

Figure 8 represents the actual, wintery weather conditions encountered in Iceland during the project. This section scrutinises various devices of the fuel cell system in the Mercedes-Benz fuel-cell-Citaro (2003) deployed in the ECTOS project. This bus was also the choice of the projects CUTE and STEP and has even been used in Beijing, China [38].



Figure 8: A fuel cell bus on its route in Reykjavik, Iceland [39]

Lately, fuel cell buses have experienced clear improvements in efficiency and technology, such as the utilisation of batteries and additional power aggregates. These vehicles

are generally referred to as fuel cell hybrid vehicles (FCHV) and use additional power sources in order to reduce fuel consumption and improve the overall system efficiency. However, the basic fuel cell system-related components in fuel cell buses can best be introduced by reviewing the fuel-cell-Citaro deployed in ECTOS. [40]

The conventional Mercedes-Benz Citaro diesel buses served as the physical basis for the fuel-cell-Citaro buses designed in 1999 – 2000. The intention of the European fuel cell bus programmes was to demonstrate that hydrogen-powered fuel cell buses could be utilised as a part of the urban transport in Europe. Thus, the main goal was not to optimise the fuel economy but to attain high reliability and durability typically required by the transport agencies. This was mainly achieved through utilising standardised series-production components available for conventional diesel buses [38]. It was presumed that appealing to the public as a dependable transit solution would boost the future development of fuel cell buses. [24]

The drive train of a fuel cell bus consists of several modules, each of which has its own function. The main devices for Mercedes-Benz fuel-cell-Citaro bus are explained in the next paragraphs.

The fuel cell system of a 12 metres long, low-floor Mercedes-Benz fuel-cell-Citaro used in the ECTOS project generates propulsion through a drive train equipped with Ballard's HY-205 P5-1 fuel cell engine. The HY-205 drive train is designed to replace the typical diesel drive train with a minimum amount of technical adjustment. The fuel cell engine uses hydrogen as fuel and feeds a compact liquid-cooled electric propulsion motor. [24] [41]

The Mercedes-Benz fuel-cell-Citaro is equipped with an engine containing fuel cell stacks in discrete cell rows. An electronic measurement system monitors cell voltages constantly. For maintaining appropriate operation conditions, the module contains air and hydrogen humidifiers, as well as their associative hardware. Specific hardware controls and handles the recirculation of hydrogen. Fuel cell stacks incorporate a special minimum current limitation, so the fuel cell system has a resistor for dumping excess electricity. Basically, in the resistor, the excess electricity transforms to heat which is then utilised in the heating or cooling units of the vehicle. Fuel cell stacks are typically mounted on the top of the roof or into the engine room. If the installation is located on the roof, as in Mercedes-Benz fuel-cell-Citaro, the bus is higher than a normal diesel-driven bus. [24] [41]

A single electric motor runs various main functions in the fuel cell system of the Mercedes-Benz fuel-cell-Citaro either directly or indirectly. An inverter converts the direct current supplied from the fuel cell stacks to 3-phase alternating current suitable for the

electric motor. The electric motor gives power to the automatic central gearbox and air conditioning compressor. The electric motor also provides power to the transmission and transmission retarder which creates additional braking power for the vehicle. Standard auxiliaries, such as brake compressor, power steering pump and a hydraulic fuel cell radiator fan pump are driven by the gearbox through drive belts. Additionally, a 24-volt electric system in the fuel-cell-Citaro provides power to various auxiliaries. [24] [41]

Furthermore, the gearbox runs a supercharger that produces pressurised air which is directed to the fuel cell stacks. The pressurised air passes the stacks and is funnelled to a turbocharger as exhaust gas. The turbocharger conserves energy from the exhaust providing more compression. An inter-cooler cools down the air to enable higher compression efficiency, as cooler air fits to a more compact space. The inter-cooler filters out contaminants of the air as well. The noise level of the fuel cell air system is diminished by mufflers on the air intake and exhaust systems. [41]

The operation of fuel cells produces excess heat that must be disposed of to maintain suitable operating conditions. The Mercedes-Benz fuel-cell-Citaro incorporates specific cooling circuits with liquid coolant. For the fuel cell stack cooling circuit, the coolant flow and inlet temperature are measured continuously while extra heat from the coolant is transferred into the atmosphere. The cooling effect is achieved through hydraulic fuel cell radiator fans and a specific heat exchanger. Cooling circuits involve the heat exchangers of the drive train, the cabin loop and the transmission retarder. The electric motor cooling oil and electric inverter are also cooled down through these circuits. For the cabin, cooling circuits provide heating. To have a proper heating for the interiors, the Mercedes-Benz fuel-cell-Citaro also provides a separate heating interface of 40 kW. The system is capable of producing heat only when the fuel cell engine is active. [41]

Quick-starting the fuel cell engine in the Mercedes-Benz fuel-cell-Citaro is only possible when the temperature of the engine is above + 5 °C. When the outside temperature falls below the given value, an electrical block heater equipped with a thermostat warms up the fuel cell stacks. Fuel cell stack insulation prolongs the cooling time and thus improves the overall efficiency of maintaining a proper temperature in the engine. [41]

PEM fuel cells are sensitive to several substances. Fuel cell may become contaminated by fuel impurities, air pollutants and cationic ions resulting from corrosion of the fuel cell system components. Particularly, low-temperature fuel cells encounter this problem. In case of contamination, the performance level of fuel cell system can drastically decrease. A single fuel cell can lose a few per cent of its average voltage level because of NO_x impurities when operating in a dirty city environment. In extreme conditions, some impurities could even cause power failures. Due to contamination and the accumulated

condensate water which occurred during the operation, the fuel cell hydrogen system is typically cleaned with specific equipment. In the Mercedes-Benz fuel-cell-Citaro, contaminated hydrogen gas along with water vapour is discharged through a diffuser into the atmosphere. The discharging occurs on start-ups and shutdowns, as well as cyclically during driving. To provide safe operation, the contaminated hydrogen is mixed with an extensive amount of air before ventilation. [41] [42]

Hydrogen has the widest range of flammable concentrations in air among all typical gaseous fuels. Thus, hydrogen can easily ignite if used against safety regulations. To be more precise, the auto ignition temperature of hydrogen is low, and it can ignite from a spark or heating. Hydrogen is an odourless, colourless and tasteless gas that necessitates leak detectors in buses for safe operation. A leak in hydrogen system could pose a threat to those around in an open air fuelling station, as well as in enclosed spaces. Hydrogen also causes metal embrittlement in pipes, gaskets and welds when continuously exposed to the gas. [43]

The fuel-cell-Citaro has nine high-pressure cylinders for storage of hydrogen. These cylinders hold 40 kg of hydrogen fuel at 350 bars at a temperature of 15 °C. The light-weight composite storage cylinders are located on the roof of the vehicle. The cylinder manufacturer guarantees the functionality of its product under the harshest environmental circumstances confronted in automotive usage. The fuel-cell-Citaro hydrogen storage system enables fast filling. [41]

30 Mercedes-Benz fuel-cell-Citaros were delivered by EvoBus GmbH in 2003 [44]. Three of these became a part of the project ECTOS as described earlier. Because these buses utilise fuel cells in propulsion, they hold some distinct vehicle characteristics. The series EvoBus design features a standing platform for the engine and transmission in the left rear area. As the bus weighs three tons more than a diesel bus, the body work is reinforced particularly from the roof area where certain parts of the fuel cell drive train and cooling system fans are situated. Thus, the most visible change in comparison to a corresponding diesel vehicle is the increase of height of the bus. The overall height of the fuel-cell-Citaro is approximately 3,700 mm. The suspension of the fuel-cell-Citaro is adjusted to efficiently carry the extra weight. [41]

3.5 *New technology – Mercedes-Benz Citaro FuelCELL*

The up-to-date Mercedes-Benz Citaro FuelCELL-hybrid buses (2010) deploy novel technologies to improve the efficiency and competitiveness of the fuel cell system. In addition to the fuel cells, the bus also deploys a 330-kg battery pack. The water-cooled lithium-ion battery pack operates as an intermediate storage for the energy generated by

the fuel cell stacks. The battery pack operates maintenance-free and offers 250 kW of power, as well as the possibility of recuperating braking energy. For smooth, efficient operation, the bus model utilises energy stored in batteries while accelerating and charges the batteries while decelerating. When driving a constant, higher speed, the Citaro FuelCELL-hybrid only utilises fuel cell stacks for energy generation; batteries sustain their charge level. [40] [45]

The Citaro FuelCELL-hybrid incorporates a fuel cell system capable of supplying 120 kW of continuous power, while consuming 10 – 14 litres of hydrogen per 100 km. A hydrogen storage capacity of 35 kg allows the bus to travel around 250 km in the fuel cell mode without refuelling. The bus control system incorporates a unit for ancillary functions that is supplied through the battery pack. An intermediate electric circuit feeds two wheel hub drives on the drive shaft with a voltage of 650 V DC. These wheel hub traction motors, similar to those of trolley buses, create a power of 160 kW in total. The peak power reaches up to 120 kW per motor for 15 – 20 seconds. The approximate service life for the fuel cell system according to Mercedes-Benz is six years or 12,000 service hours. [40] [45]

The new Mercedes-Benz Citaro FuelCELL-hybrid provides the low-floor feature with a floor height of 370 mm. The boarding height for three different doors is a little less than the actual floor height. The bus model has a capacity for 76 passengers, 26 of which can travel using a seat. The height of the bus is 3,400 mm. This is about 300 mm lower than the height of the earlier fuel-cell-Citaro (2003). The length of the bus has remained about 12 metres. [45]

3.6 *Hydrogen infrastructure basics*

The fuel cell technology in automotive usage involves an infrastructure for producing, storing, as well as transporting and dispensing hydrogen. The first step, to produce hydrogen, incorporates several possible methods: coal and biomass gasification, natural gas reformation, water splitting by high-temperature, as well as water and photo-electrolysis and biological processes [18]. After production, hydrogen must be stored in a specific manner before transporting it to a place for distribution or end use. A dispensing system services the end user at a hydrogen fuelling station which functions basically the same way as common gasoline or diesel fuelling stations.

Storing hydrogen can be implemented in several ways. Liquid state and high pressure storages, as well as a storage utilising metal hydrides are the possible methods. Storing hydrogen in liquid state requires an extremely expensive cryogenic storage which necessitates a storage temperature that is below hydrogen's boiling point – i.e., approximately

– 253 °C [46]. The liquid state hydrogen storage makes it possible to store hydrogen in a smaller space than any other method of storage. [43]

The second storage method is based on bonding hydrogen molecules with metal hydrides. To extract hydrogen from the compound requires heat. The compound can only be stored in small quantities and holds slow intake and outtake kinetic properties, which is a clear problem in automotive usage. [43]

It is also possible to store hydrogen in high pressure tanks. This method has been widely used in fuel cell bus projects described earlier. The typical pressure used varies around 340 – 690 bars. High pressure tanks have a couple of superior characteristics which distinguish them from other storage methods. High pressure system can be charged and discharged quickly; the charge time depends solely on the compressor. This particular method of storing hydrogen is also less expensive to implement in small-scale refuelling sites than the previous ones. [43]

There are two main categories in hydrogen transport. Hydrogen in a gaseous form has been transported via pipelines for more than 50 years. Some countries in Europe and a few states in the United States have pipelines for industrial usage. The difference between hydrogen pipeline and a natural gas pipeline exists in the material choice. Pipelines for hydrogen transport are made of non-porous materials (e.g., stainless steel), whereas natural gas pipelines often involve plastic materials that are porous for hydrogen. Replacing old pipelines or constructing a new pipeline network with transport and distribution branches would incur significant costs. Building a pipeline for hydrogen is estimated to incur roughly six times higher expenses than a natural gas pipeline, mainly because of the lower energy density of hydrogen. [18]

Hydrogen can also be transported by truck or ship in a liquid form. However, the expensiveness of the hydrogen liquefaction process restrains the transport of liquid hydrogen. Nevertheless, it has been estimated that the liquefaction costs reduce significantly by 2030. [18]

Dispensing hydrogen to transit or single-occupancy vehicles is possible at a hydrogen refuelling station with specific equipment similar to gasoline or diesel dispensing systems. Stations typically offer gaseous or liquid hydrogen. The hydrogen is produced either on-site or received from centralised plants. [18]

It is important to ensure the safety of the refuelling station and control the hydrogen flow. The dispensing system includes a leak detection system and a flow meter. Because of the wide flammability range of hydrogen, it is necessary that the leak detector detects hydrogen concentration levels in air down to one percent. Safety regulations concerning

the refuelling stations relate to the general design and equipment of the station, as well as barrier walls, weather protection and on-site hydrogen production. [43]

3.7 Costs related to fuel cell buses and the hydrogen technology

Fuel cell buses can be seen as a rather newly innovated application, so the prices between market areas and suppliers vary a lot. The lack of proper series production has kept vehicle costs high even though there has been a trend of reducing prices. Comparing to a diesel bus, the vehicle body of an FCV requires only a few significant changes (i.e., the increase in height and reinforcement of the bus structure), and thus, does not contribute to higher costs. Notable expenses arise from the fuel cell system, as well as hydrogen production, distribution and storage.

Fuel cell buses will most probably be the trend-setter for fuel cell usage in the automotive industry. In general, buses offer a great platform for proving whether technical solutions are functional since they are often operated long distances in a frequent manner. It is estimated that the cost of a fuel-cell-Citaro prototype bus in the CUTE programme was around EUR 1.3 million. The diesel version of the bus cost approximately one million Euros less. The STEP project in Perth, Australia deployed fuel cell buses priced around AUD 2.0 million in 2006, that equals – considering the exchange rates of March 2006 – approximately EUR 1.2 million [47]. Diesel buses in Perth cost around AUD 360,000 (\approx EUR 218,000) [47], which along with the price information from the CUTE project implies that the price of a fuel cell bus has typically been fivefold the level of the diesel alternative. [48] [49]

Regardless of the substantially higher price of fuel cell buses, the overall prices for fuel cell buses have decreased in recent years. In 2007, Connecticut Transit in the United States acquired a fuel cell bus (manufactured by Van Hool) that was 25 percent less expensive than a comparable bus delivered to AC Transit not more than two years before. Prices for buses have typically been higher in North America than in Europe. An estimated price for a fuel cell bus in 2005 ranged from USD 1 to 3 million (\approx EUR 805 – 2,410) [47] [50]. Fuel cell bus prices altered a lot since they were hand-built prototypes utilising pre-commercial, obviously expensive technology. [33] [51]

Fuel cell buses in various demonstrations have been prototypes. This reflects in the maintenance facilities and fuelling stations specifically engineered for fuel cell bus usage. Californian transit agencies (i.e., AC Transit, VTA and SunLine) had their maintenance facilities built between 2000 and 2006. Facilities were built to service the varying needs of the fuel cell buses involved. SunLine maintenance facility for two fuel cell

buses is a ventilated tent built right behind the original maintenance building in 2000. Sensors and a sound alarm for hydrogen leaks were used for safety purposes. This light construction incurred expenses of USD 50,000. On-site generated hydrogen by a natural gas reformer at the SunLine fuelling station is provided at approximately 340 bars. The storage on the site can hold 180 kg of hydrogen. The reformer purchase and installation cost initially USD 750,000. A six-year maintenance agreement was made for USD 300,000 in 2006. [14]

VTA maintenance built a larger facility with a fuelling station and a bus wash. The overall costs rose to USD 4.4 million. The facility is a free-standing building with two maintenance bays, storage and working space. The building has equipment for hydrogen and flame detection, as well as a sufficient ventilation system and antistatic coating on doors. The separate initial cost for the fuelling station at VTA was around USD 480,000 after which the agency has paid the station owner contractually USD 4,400 per month for the maintenance of the fuelling station equipment. The station features a 34,000-litre cryogenic liquid hydrogen tank and a possibility of dispensing gaseous hydrogen at around 410 bars. [14]

AC Transit's approach was slightly different from the implementations of SunLine and VTA. The maintenance facility for fuel cell buses at the transit operator's premises was implemented inside an existing maintenance building, separated with a firewall. Other safety equipment incorporated easily opening doors; ignition-free heating; grounded, antistatic floors; and hydrogen detection, as well as other sensors. As a safety rule, fuel cell buses entering the maintenance facility are not allowed to carry gaseous hydrogen at more than 40 bars. Modification costs to the original maintenance facility totalled about USD 1.5 million. The fuelling station at AC Transit includes storage for 366 kg of gaseous hydrogen with two dispensers. [14]

The main option for storing hydrogen in FCVs is to use high pressure tanks. The technology for storing gaseous hydrogen is in a mature state. The production of carbon fibres has existed for a long time and its price is not to be lowered significantly. Series production of FCVs could reduce the cost of hydrogen high pressure tanks to USD 500 – 600/kg H₂. Considering the fuel storage capacity of the Van Hool A330 FCB (i.e., 50 kg of hydrogen fuel), the total costs for manufacturing and assembling the storage would then approximate USD 25,000 – 30,000. [18] [14]

Hydrogen production costs depend on the production method and the scale of production. Two interesting alternatives to produce hydrogen are electrolysis and natural gas reformation. In 2007, the cost of producing hydrogen by electrolysis was typically above USD 3.6/kg, while the production cost of large-scale natural gas reformation varied around USD 1.2 – 1.8/kg. At smaller reformation plants, the price was more similar to

that of hydrogen production by electrolysis. Decentralised small-scale production could have exceeded USD 6/kg. [52]

Distribution of hydrogen incurs less significant costs than the production. Gaseous hydrogen distributed through pipelines incorporated expenses of around USD 0.12 – 0.24/kg back in 2007. Transporting liquid hydrogen long distances by ship involved greater costs than transporting liquid natural gas because of the cryogenic technology and losses related to it. Refuelling stations together with the transport and distribution of hydrogen increased the overall infrastructure costs of hydrogen by some USD 0.6 – 1.44/kg. [52]

3.8 *Environmental issues*

Fuel cell buses generate exhausts very limitedly. Since water and heat are the only by-products generated during the operation of a fuel cell, the rubber tyre dust along with a slight amount of NO_x emissions from possible on-board natural gas reformation are the only detrimental street-level emissions generated by a fuel cell bus. The production of hydrogen generates non-local emissions, and thus, extensively assesses the gross level of overall or well-to-wheel emissions occurred from the use of hydrogen fuel cell technology. Fuel cell buses can promote the development of a healthy environment by improved fuel economy, reduced exhausts, as well as advanced pedestrian and passenger comfort levels (i.e., cleaner city surroundings, reduced noise and vibration). [48] [53]

Fuel cell buses often feature higher fuel economies than diesel buses. Thus, FCBs provide greater vehicle mileage and save energy. However, the fuel cell buses in the demonstration projects – e.g., ECTOS and CUTE – weighed up to three tons more and consumed more equivalent fuel in comparison to normal diesel buses. The extra weight on the buses mainly occurred from the fuel cell drive train and air conditioning system [38]. Despite the lower fuel economy, the average power train efficiency of the fuel cell buses varied around 34 – 37 percent which beats the efficiency of fuel input to power the gearbox of a normal ICE. The objective for the ECTOS and CUTE projects, however, was not to strive for optimal fuel economy. [24]

Some demonstration projects have shown that the fuel economy of fuel cell buses can be significantly better than that of diesel buses. Figure 9 represents the fuel economies attained in the aforementioned demonstrations in the United States. The best fuel economy was attained at SunLine where the baseline buses were powered by compressed natural gas (CNG). VTA fuel cell buses, on the contrary, presented fuel economies about 12 percent lower than diesel buses on the site. The deteriorated fuel economy of the fuel cell buses at VTA resulted partly from the absence of both hybrid technology

and braking power recuperation. These technical advancements could easily have improved the fuel economy. [14]

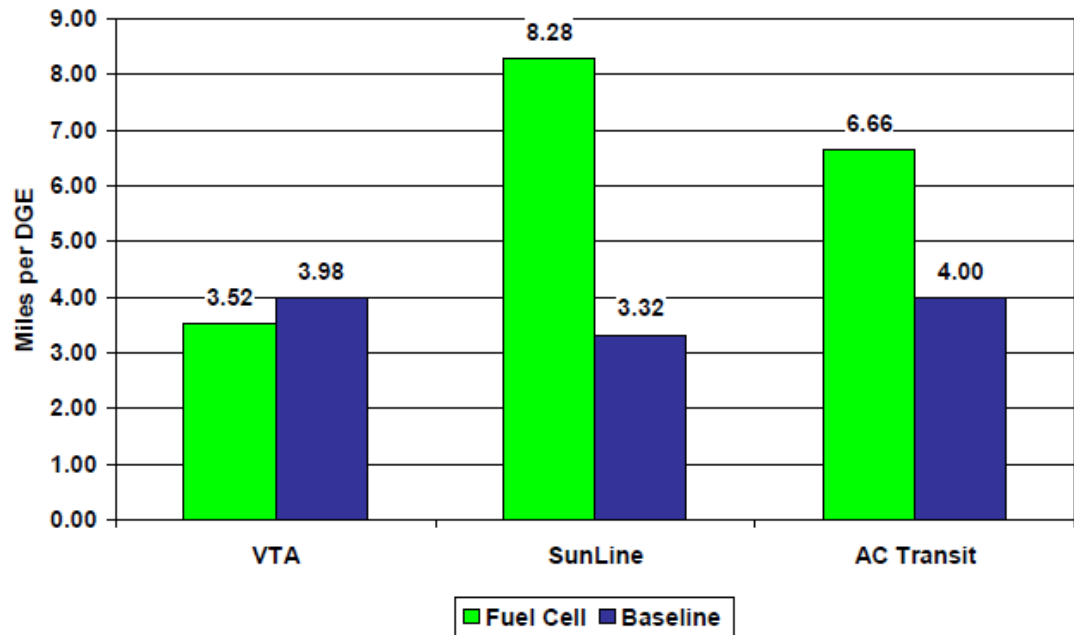


Figure 9: Fuel economies for fuel cell and baseline buses in the demonstration programme in the United States (diesel gallon equivalent, DGE) [14]

While hydrogen fuel cell buses can positively contribute to the fuel economy of public transport, and therefore, promote sustainability, hydrogen production alone sets environmental challenges. Hydrogen production generates emissions in notable amounts. Table 2 presents carbon dioxide emissions generated by alternative hydrogen production methods. The zero emission case only becomes possible when the electricity needed in the electrolysis process is produced with renewable energy sources, which would eliminate carbon dioxide emissions. [43]

Table 2: Carbon dioxide emissions for various hydrogen production methods [43]

Production Method	kg CO ₂ /kg H ₂
Coal Gasification	19
Natural Gas Reforming	17.6
Electrolysis – Non-Renewable Power Source	12
Electrolysis – Renewable Power Source	0

A kilogramme of hydrogen contains approximately 120 MJ of energy, while a kilogramme of US conventional diesel holds circa 43 MJ [54]. While diesel weighs roughly 0.85 kg per litre and causes CO₂ emissions of circa 8.2 kg per a US gallon [43], the amount of CO₂ emitted per a kilogramme of diesel equals 2.5 kg. These figures are based on complete combustion of octane-rich diesel fuel. Accommodating the information in Table 2 and the latter assumption about diesel-related emissions, the production of hydrogen seems to generate significantly more CO₂ emissions than a diesel ICE in active state, but it is not to forget that the energy content of hydrogen is nearly three times higher than that of diesel fuel. In other words, 120 MJ of diesel burnt in an ICE would generate roughly 7.0 kg of CO₂. The amount of emissions for a diesel ICE thus is below the emissions from nearly any kind of hydrogen production. However, hydrogen production sites can significantly reduce emissions by utilising carbon capture methods. No means of carbon capture are recognised in the calculations of Table 2. [43]

4 Battery-electric vehicles – buses

4.1 History and status of electric vehicles

The first electric vehicle (EV) was introduced in 1834. In 1890s, various producers manufactured EVs in America, Britain and France. Due to limitations and restrictions of batteries, the earlier EVs have disappeared from the automotive markets since 1930. In the beginning of the 20th century, the active and growing deployment of ICEs strongly diminished the use of EVs. However, there has been progress with electric vehicles since the 1970s as the energy crisis set the development in motion. The development of EVs was given an additional impetus some 20 years later by various energy policies particularly driven in California, the United States to reduce atmospheric pollution [55]. Later on, mandates for zero emission vehicles have increased the popularity of EVs. In London, there were around 900 new EVs in use in 2007. Currently battery-electric systems are, however, mainly used for small vehicles and short distances. [56]

At present, batteries are often utilised to offer additional capacity in buses, as in HEVs which utilise batteries as a secondary equipment for more efficient, less fuel consuming propulsion. However, more extensive use of batteries is in sight. For instance, trolley buses could utilise batteries on peripheral parts of their routing. This would save a great amount of costs typically incurred by the construction of an overhead wire network. Such solutions have been in use in San Francisco, Vancouver and Beijing. Simultaneous utilisation of overhead wires and batteries can provide a beneficial solution to transit agencies, especially, when vehicles utilising those technologies share the same driving corridors. Driving through the same exact places would enable centralised recharging of vehicle batteries through trolley poles. [57]

It is noteworthy that the reliability of a transport system is increased when utilising several parallel power sources or propulsion systems. However, also pure battery-electric vehicles (BEVs) may possibly become an efficient, economic alternative for transport fleets in the future. With a proper charging infrastructure or advanced battery-swapping stations, it could be possible to create transport systems solely dependent on batteries.[57]

4.2 The most prominent battery technologies for electric vehicles – Li-ion

Nearly all of the batteries used in electric cars on the market are based on some sort of lithium-ion (Li-ion) technology. Lithium, compared with any other chemical element, holds the lowest standard redox potential, and thus, is the strongest reductant. Therefore, lithium offers the potential to be the best material for batteries regarding the energy density (Wh/kg). Li-ion batteries are rechargeable, efficient, as well as reliable. They are suitable for both high-energy and low-energy applications. Concerning electric vehicles' propulsion power management, the automotive industry will naturally focus on high-energy solutions. [16] [58]

The family of Li-ion batteries comprises battery characteristics that employ various chemical combinations of anode and cathode materials. Each combination has its advantages in terms of energy density and power density (W/kg), battery lifetime, safety, costs etc. The energy and power characteristics exclude each other to some extent since increasing the energy density typically decreases the power density of a battery pack. In other words, the larger the reactive area inside the battery the thinner the wirings for power transfer. [16] [59]

All the Li-ion technologies require proper monitoring, balancing and cooling systems in order to manage the chemical energy release, thermal stability and the lifetime of the battery cells. The currently most prevalent technology used in consumer applications is lithium-cobalt oxide (LCO) which, however, incorporates some fundamental safety problems. On the contrary, various promising technologies – i.e., lithium-nickel-cobalt-aluminium (NCA), lithium-nickel-manganese-cobalt (NMC), lithium-manganese spinel (LMO), lithium titanate (LTO) and lithium iron phosphate (LiFePO_4 or LFP) – are showing their potential to the automotive industry. [59]

Novel electric vehicles need a reliable power source with high energy density and long working life. One of the most promising technologies for future automotive applications is lithium iron phosphate technology. LFP technology enables manufacturing of relatively lightweight batteries that withstand high ambient temperatures up to 60 °C. LFP cell chemistry offers high reliability and safety levels – i.e., LFP battery will not explode or catch fire. Various vehicle battery manufacturers are favouring LFP technology, and thus, it is reasonable to discuss the advantages and disadvantages of the technology more in detail. [60] [61]

LFP batteries are among the most highly developed battery technologies at present. They avoid the various shortcomings of other technologies. Batteries do not suffer from any memory effect and they can be recharged at any time. The possibility of rapid re-

charging of LFP batteries supports their use in vehicles. LFP batteries attain a high discharge rate with no voltage sag (i.e., flat discharge rate). Additionally, the self-discharge level of one cell typically stays under one percent per month. LFP batteries can be left standing in storage even partially discharged. [61]

LFP batteries are maintenance-free for the lifetime of the battery pack, which enables easy electric vehicle maintenance. In addition, the solid construction of LFP battery cells prevents damage occurring from the vibration of the vehicle. Containing no toxic heavy metals, corrosive acids or alkaline, the LFP battery chemistry is the most environmentally friendly option available. [61]

LFP batteries can realistically provide an energy density of 140 Wh/kg, the cyclical lifetime of batteries being around 2,000 – 3,000 charges at 80 percent depth of discharge [61] [62]. After the lifespan of the LFP battery, the active materials inside the battery can be removed and recycled in a safe, environmentally friendly manner. Lithium iron phosphate can be treated with low temperature methods to recover the potential for battery usage. The treated LFP acts similarly to the primary material. Consequently, LFP is a durable material which can be recycled and reused. [63]

Nonetheless, LFP technology is not the only suitable Li-ion technology for automotive usage. For instance, vehicle manufacturers might easily end up favouring lithium titanate technology in the future. Using titanium instead of graphite on the cathode side of the battery cell – contrary to the LFP technology – lengthens the cyclical lifetime and improves the power density of the cell. Despite the decrease in energy density, titanium offers great battery cell durability. Properly developed, LTO batteries could possibly go through 25,000 recharge cycles without significant degradation of battery cells. [16] [64]

4.3 *Battery manufacturers*

Various companies worldwide manufacture high-capacity, high-power Li-ion batteries. The next paragraphs will briefly introduce some of those manufacturers to give a view of the Li-ion battery market base. One of the international battery manufacturers is the Chinese Thunder Sky. The company has, in its own words, created some momentum among electric bus production in China and Taiwan. Thunder Sky, doing cooperation with a Chinese First Automobile Works, has a short-term goal of manufacturing 25,000 electric buses annually. Buses would be used in Chinese metropolises. [65]

On 14th April 2010, the Mitsubishi Motors Corporation released news about Lithium Energy Japan (LEJ) constructing a new plant to Ritto, Japan to begin full mass produc-

tion of Li-ion batteries in 2012. LEJ has announced that it aims for annual battery production enough to cover 100,000 small EVs. [66]

A North American-based company, Altair Nanotechnologies Inc. manufactures batteries based on a proprietary, nano-structured lithium titanate. Currently, they guarantee over 12,000 charge cycles (i.e., a lifetime of around 15 years) to be reached with their products. Within the automotive industry, the company channels its interest into HEVs. [67] A123Systems is another company manufacturing high-power Li-ion batteries for transport. The company, founded in the United States (2001), has patented a Nanophosphate™ technology that utilises nanoscale materials. A123Systems has developed a 20 Ah Prismatic battery cell that should offer very low cost watt-hours for battery-electric transport applications. [68]

In France, a joint venture Johnson Controls-Saft Advanced Power Solutions launched in 2006 is concentrating on high-tech nickel-metal hydride (Ni-MH) and Li-ion batteries for hybrid electric and electric vehicles. In January 2008, a new manufacturing facility was opened for Li-ion batteries in Nersac, France. The joint venture has already entered into a contract with a few international car manufacturers. [69]

Bosch and Samsung established an equally owned joint company, SB LiMotive, in 2008. The company has an ambitious target for developing, manufacturing and selling Li-ion batteries for automotive applications. Battery cell production will start in 2011. The amount of investment costs incurred will rise up to USD 500 million over the first five-year period. [70]

In Finland, the European Batteries Ltd. is starting LFP battery manufacturing in a newly constructed facility. Starting in the first half of 2010, the operation should expand to enable production of 300 MWh of battery capacity by 2012. European Batteries will manufacture both battery cells and battery control systems in the same facility, which enables convenient circumstances for pre-testing and therefore reliable battery operation. [60]

4.4 *Battery-electric bus implementations*

The development of battery-electric buses (BEBs) has been rather slow despite the extensive research and development efforts that have been devoted to improving various battery technologies. To date, BEBs have mainly been used for slow speeds and short distances – e.g., shuttle service. During the 1990s, commercial battery technologies were not yet able to make a breakthrough to be a natural choice for bus manufacturers. They lacked some power and offered a poor range of operation. Now, following the latest

progresses with Li-ion battery technologies, batteries provide a possibly beneficial, reasonable alternative to other power sources. [50]

Battery-electric buses obtain the power for their movement from similar electric traction motors to fuel cell buses and trolley buses. Less noisy, more efficient electric motors provide their maximum torque already at lower speeds, which results in extremely applicable acceleration rates for generally discontinuous bus traffic. Regeneration of braking energy and a complex electric drive control system are typically included in BEBs as well. [50]

BEBs are typically either recharged or their batteries are swapped to other ones at a battery-swapping station. The time of recharging varies regarding the battery capacity and the output of the charger. Charging can be implemented at various power levels, depending on the infrastructure, vehicle type, charging time etc. For convenient operation, bus transit agencies could utilise a fast-charging station or a battery-swapping station at the end of or in the crossings of bus lines. [50]

Earlier, due to the excess weight and limited range caused by the batteries, the majority of BEBs in service were small-sized. For instance, until 2005, nearly all the North American BEB projects utilised under 7-meter electric minibuses. Utilised battery technologies generally involved no Li-ion battery technology. The largest fleets could be found in Santa Barbara, California and Chattanooga, Tennessee. [50]

One of the few main suppliers of electric buses to North American projects has been Ebus. The fast-charging capable battery-electric bus of Ebus cost USD 298,000 (\approx EUR 204,000) in 2008, the charger price being USD 58,000 (\approx EUR 39,600) [47]. This small-size bus offers room for 22 sitting passengers and 10 standing passengers, and thus, cannot compete in space with an average bus. The basic battery system of the bus consists of low maintenance nickel cadmium (NiCd) batteries that provide roughly 70 km of operation between charges. The lifetime expectancy of the Ebus BEB batteries is said to be up to 2,000 cycles on the company website. [71]

In August 2010, Link Transit, the public transport provider serving two separate counties in central Washington State, let know about its acquisition of five Ebus electric trolley buses equipped with lithium titanate batteries. Also two fast-charging stations would be involved in the acquisition. Batteries would serve a range of a little less than 20 kilometres with at least a five-year cycle life. Charging the batteries to 80 – 90 percent of the full capacity would only take from five to seven minutes. [72]

A cooperative demonstration programme for a Zinc-Air battery bus was initiated in 1998 in Las Vegas, Nevada from the initiative of various partners, one of which was

FTA. The patented Zinc-Air battery technology was implemented on a full-size bus frame. The bus represented one of the very first full-size, full-electric buses driven on public roads worldwide. In the Zinc-Air battery system, power was produced through oxidation of zinc. In the programme, the Zinc-Air battery pack supplied 99 kW of power and 312 kWh of energy. For more powerful traction, the bus had one smaller NiCd battery pack that offered 125 kW of power. The Zinc-Air battery system typically required mechanical removal and replacement of spent battery packs. [73]

In the European markets, electric buses have existed already for more than 20 years. In Italy, for example, small BEBs have been used since 1989. Tecnobus, an Italian minibus manufacturer, is seemingly the main provider of small electric buses in Europe. Italy's transport fleets alone account for over 370 electric minibuses delivered by Tecnobus. The basic model of the minibus is shown in Figure 10. Other European countries implementing electric buses from the same company include France, Norway, Portugal, Spain and the United Kingdom. In Rome, Italy, electric minibuses total around 1,500,000 vehicle-kilometres per year carrying 27 passengers at maximum. The rechargeable batteries of the Tecnobus buses are based on lead-acid technology enabling a range of 45 km. [74] [75]



Figure 10: Electric Gulliver (Tecnobus) - basic model [75]

Regardless of the slow development within the electric bus industry, BEBs have recently attracted more attention, and especially, more full-length electric and hybrid electric buses have entered the market. For instance, the city of Xinxiang in Henan province, China welcomed an 11.6-meter electric bus launched by Yutong in February 2010 [76].

In February 2008, Proterra, an innovator and manufacturer of commercial transit solutions, commenced a clean bus tour in California. Proterra introduced a fast-charge battery-electric bus EcoRide BE35 that would create savings of USD 310,000 per bus in

total lifetime fuel expenses. While offering a clean ride to Californians, Proterra's bus involves a battery pack that can be fully recharged in less than 10 minutes. The EcoRide BE35 results in up to fourfold fuel economy levels compared with an average urban diesel bus. The bus can be run in pure battery-electric mode around 45 km or with any small APU through a convenient vehicle control system. A regenerative braking system and an up-to-date battery management system optimise the energy efficiency and system life in Proterra's BEB. [77] [78]

One of the latest introductions of Li-ion technology combined with an APU is New York City Transit's addition to its bus fleet; three hybrid electric buses deploying DesignLine's spinning turbine that recharges the batteries. The vehicles are not counted as pure battery-electric buses but are still capable of running on pure battery energy for extended periods of time. The contract with Designline, a Charlotte, North Carolina-based manufacturer, includes a 12-year warranty for both the battery pack and turbine. The bus measures around 10.7 metres in length, carrying up to 37 sitting and 30 standing passengers. The cost per bus in December 2009 was USD 559,000 (\approx EUR 383,000) [47]. The pilot project of three buses may lead to a kick-off of a broader use of DesignLine's buses. The city has planned to order 87 additional buses, if the bus type proves to be successful. DesignLine operates buses in Charlotte and Baltimore as well. San Diego and Los Angeles joined the group in 2010. Besides operating in the United States, the company runs buses in Australia, Japan, New Zealand and the United Kingdom. [79] [80]

Adelaide, Australia has advanced in bus systems through a solar power recharging station and a solar-powered electric bus. This pure electric bus carries up to 40 passengers and relies solely on solar power production. It stores energy in Swiss-made Zebra batteries utilising sodium-nickel chloride technology. The bus offers 200 kilometres of travel distance between recharges in a common city environment. [81]

Various existing propulsion systems utilised in buses commonly deploy some kind of an APU. Thus, a full-size, pure battery-electric bus is not a common sight in passenger traffic, though not an excluded option. For instance, Astonbus Inc. provides BEBs depending solely on batteries. According to the Astonbus web page, their 12-meter, 19.5-tonne electric bus E-City 12.0 incorporates an LFP battery pack of 360 kWh. The battery pack with a rated power of 100 kW takes 6 – 8 hours to recharge. The bus provides a capacity for taking 61 passengers on board. [82]

4.5 *Plug-in hybrid electric vehicles – implementation in bus traffic*

Plug-in hybrid electric vehicles (PHEV) along with HEVs form a middle stage for pure BEBs in the automotive industry. Batteries provide these vehicles more efficiency but not all the energy needed for propulsion. PHEVs are a grid-connectable version of HEVs. The power grid is utilised for recharging the vehicle batteries. PHEVs commonly carry more battery capacity than basic HEVs but not nearly as much as typical BEVs operating solely on batteries. The plug-in functionality of PHEVs enables advanced fuel economy compared to HEVs. [83]

PHEVs usually carry an ICE and an electric motor. These two operate either in parallel or in series. A parallel PHEV entails a direct connection between the engine and the wheels, as well as between the electric motor and the wheels, whereas a series PHEV only uses the traction power provided by the battery-powered electric motor. A series PHEV system runs the ICE only to recharge the batteries. In a PHEV, batteries are recharged from the electric grid, by regenerative braking or by the ICE. Figure 11 illustrates the operation of series and parallel PHEVs. Compared with other electric-drive vehicles, one major advantage of PHEVs is fuel flexibility. The consumption ratio of electric energy and liquid fuel can be addressed according to the needs of the user. PHEVs can be run in pure electric mode, only on liquid fuel, or simultaneously on both. [84]

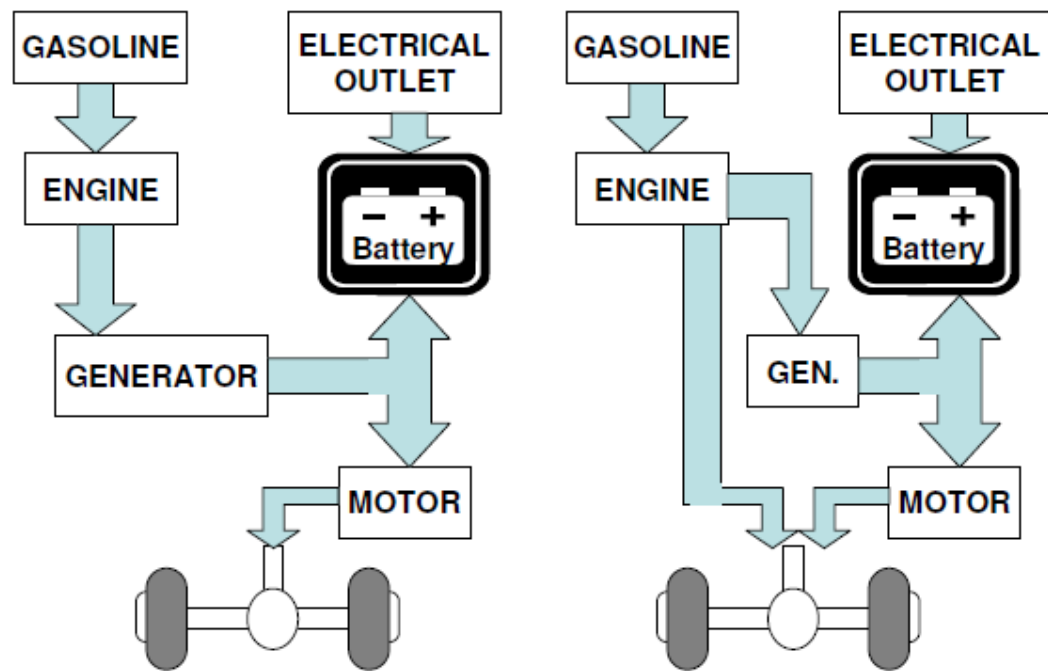


Figure 11: Series vs. parallel PHEV drivetrain design [84]

The United States Department of Energy partially funded a Hybrid Electric School Bus (HESB) programme a few years ago. The programme promoted the use of PHEV buses in school traffic. A feasibility study (Pritchard et al., 2005) of the HESB programme showed that PHEVs are profitable over the lifetime of the vehicle in comparison to conventional diesel buses. The major practical challenges for PHEVs turned out to be the optimisation of battery lifetime and high initial vehicle costs. [85]

4.6 Common challenges for vehicle battery technologies

A few essential problems restrict the use and prevalence of battery-electric vehicles. The commercial viability of BEVs will be greatly influenced by the cost of vehicle batteries. At the moment, costs are so high that even if battery manufacturers could solve the basic technical challenges batteries confront, the prices of batteries could still exceed reasonable levels. [59]

The price level of an automotive Li-ion battery pack is estimated to be around USD 1.0 – 1.2 per watt-hour (Boston Consulting Group, 2010) as sold to original equipment manufacturers (OEM). Another source (Biomeri Oy) claims that the price of a watt-hour of energy produced by an LFP battery ranged from EUR 0.25 to 1.3 in 2009, depending on the quality and battery characteristics. Take a price of EUR 1.0 per watt-hour. The

total cost of a typical 25-kWh battery pack deployed in small electric cars would equal EUR 25,000. Such a price level is extremely high and uncompetitive. However, price reductions are anticipated in future. [16] [59]

Another substantial question to overcome concerns the battery infrastructure: whether the battery pack of a vehicle would be replaced with a newly charged battery pack on a battery-swapping station, or on-board rechargeable batteries would be fixed to the vehicle. The latter would entail detaching and replacing the battery pack after its lifespan. Current issues with battery charging for both passenger cars and heavy-duty transit vehicles must be addressed to attain commercial profitability.

Vehicle batteries are still afflicted by long charging times. It takes from 10 to 12 hours to charge an average 30-kWh car battery using an average one-phase distribution network power outlet (230 V). To charge the same battery pack in less than 30 minutes would take a specific charger of over 50 kW. Ultra-fast-charging has been planned as well. A 250-kW charger could recharge a 30-kWh battery pack in only 6 minutes. [86] Despite the fact that it would take such a long time to charge the batteries with a typical slow-charging solution, using fixed batteries would possibly be easier and more convenient for private vehicle owners, as battery-swapping would incorporate additional standardisation requirements and logistical complexity. [59]

The problems with battery costs and charging times accumulate in heavy-duty vehicles whose battery capacity is notably greater. Larger vehicles, such as transit buses, may require an approximately tenfold battery capacity compared to smaller passenger cars. This would signify battery prices and recharging times of around ten times greater than what is presented above. Charging at home, workplace, car parks, curb side, as well as shopping centres may work for small electric vehicles, but for transit bus fleets and larger vehicles, the charging infrastructure must be centralised and specifically planned taking into account decisive matters, such as vehicle routing. Buses typically operate long hours with short breaks between shifts. Recharging or swapping batteries of BEBs should happen quickly, without diminishing vehicle's availability. A well-placed battery-swapping station could provide large vehicles a reliable, practical alternative. Examples of automated, centralised battery-swapping infrastructures exist. PuroNovo, a Finnish company specialised in industrial automation, is already marketing its battery-swapping system [87]. [86]

Not only have the cost issues and charging-related matters hindered battery-electric vehicles' capability to strongly enter the automotive market. It is extremely challenging to engineer batteries to function properly in a wide range of temperatures without affecting the battery performance. This is especially the case in Finland, where the weather ranges from hot summer to freezing winter. OEMs could prefer an approach where countries

with cold weather conditions would be provided with battery-electric vehicles equipped with proper insulation and heating, whereas countries with hot climates would be offered vehicles relying on battery technology based on electrolytes and materials allowing high temperature storage. Nonetheless, such an arrangement would prevent battery-electric vehicles to be moved across regions. Thus, OEMs are likely to favour a performance disadvantage or higher system costs to avoid mobility restrictions. [59] Contrary to the thoughts about high mobility, several countries deploy electric mobility in vehicle fleets designed to serve a certain area inside a city or a region. For traffic arrangements, where vehicles stay inside a particular area, implemented vehicle models could easily be location-specific designs that serve best in the prevailing, local conditions.

4.7 *The batteries of an electric vehicle as energy storage*

While using electric energy, a pure battery-electric vehicles' emission profile is similar to trolley buses. The energy produced at a generation plant is consumed by the electric motors of the vehicle practically generating no exhausts. However, vehicle batteries can be constructed to feed energy into the power grid. Thus, grid-connectable BEVs along with PHEVs can contribute to electric utilities and power grids by providing additional energy storage. For an electric utility or power grid, deploying vehicle power would contribute as system benefits, such as reliability and lower costs. Vehicle battery storages could also facilitate more straightforward integration of intermittent, renewable energy production – e.g., wind energy and solar energy. Generally, battery storages can be utilised in smoothing variable power generation. [88]. [89]

The described way of providing energy is often referred to as vehicle-to-grid (V2G) service. During the peak demand of the day, typically around 6pm when high levels of power consumption are expected, batteries connected to the electricity network could serve as peak reserves. V2G in peak power might be economic but still difficult to arrange in practice due to on-board storage limitations. Secondly, vehicle batteries could offer power to the grid as a spinning reserve in case of unexpected outages. A spinning reserve is the fastest, and thus, the most valuable way of providing additional power to the grid. V2G could offer a highly competitive spinning reserve base since the direct costs incurred from idling batteries are insignificant. Thirdly, the storage could be used to fine-tune the supplied frequency and voltage in real-time by matching generation to load demand – i.e., regulation. At night-time, the vehicle batteries could be charged using free power generation capacity. [62] [90]

The V2G service could reduce power grid infrastructure costs. The use of vehicle battery capacity could postpone acquisitions of transmission lines, transformers and other

power system components, as well as their upgrade. Additionally, using batteries for the purposes of power distribution and electric utilities could result in protection of end user devices through increased power quality. [62] [88]

In contrast to a stable, fine-tuned charging infrastructure, uncontrolled charging of electric vehicles in the Finnish power grid could easily necessitate infrastructure reinforcements. Especially, the low voltage distribution network would require new arrangements. Moreover, the transmission of electricity could become more expensive. But if the electric vehicles' charging infrastructure is adequately developed, transmission prices of electricity could even be reduced. In case of intelligent charging infrastructures, the power consumption of rechargeable electric vehicles would not create significant need for additional power generation. An intelligent charging system could actually enable more environmentally friendly power generation by decreasing the need for other short-term power production facilities – e.g., a gas turbine as a spinning reserve. [16]

Although batteries can be facilitated in several ways to serve the electric grid, the implementation of a highly developed, controlled system between vehicle batteries and the power grid is far from simple. From a realistic point of view, a large amount of batteries pose a clear issue to be examined more thoroughly. Charging various vehicle batteries would require a substantial amount of power input and adequate capacity, especially, in electricity distribution networks. Intelligent charging systems may be the answer somewhat later, but the present situation offers more or less undeveloped solutions for charging. Particularly, problems are expected in context of blocks of flats or offices. For instance, fuses and cables may have to be replaced in several buildings where electric vehicles are going to be charged. Though in Finland, several houses have heating outputs, which might help the creation of electric vehicle charging points. Electrotechnical factors should be discussed and researched more in detail to form a solid base for large-scale electric mobility implementation in Finland.

5 Comparing transit bus technologies

5.1 In general

This study concentrates on vehicles capable of utilising electric energy as propulsion power. Various transit bus technologies have been discussed Chapters 2, 3 and 4. This section aims for scrutinising and condensing the most relevant differences between these technologies. The purpose is to revise the identifiable characteristics of each vehicle technology offering extra details and more compact information than in previous sections. To understand the prevailing differences between the technologies, the basic figures of an average diesel bus are taken into comparison where needed. Chapter 5 is partly adaptable to all sorts of vehicles, not only buses.

5.2 Comparison of vehicle technologies

Table 3 describes the technological characteristics of hydrogen and battery-electric vehicles, as well as trolley buses. Convenience and usability, as well as the restrictions of the technologies are observed through a simple evaluation.

Table 3: A comparison between electric vehicle technologies (vs. diesel vehicles) [3] [91]

	Vehicle technology		
	Trolley bus (overhead lines)	Fuel cell vehicle (hydrogen)	Battery-electric vehicle
Energy conversion efficiency	+(no temporary storage; transformers and lines create losses)	--	+
Volumetric storage density	++	+	--

Technological availability	o (several manufacturers)	-	-
Additional infrastructure	- (?) (overhead lines; supportive structures)	- (?) (storage; dispensing)	- (?) (recharging; battery-swapping)
Range	+ (depends on the infrastructure)	o	--
Life cycle (<i>c</i> stands for the charge-discharge cycle of a BEV)	+ • 16 – 20 years	- • PureMotion® Model 120: 5,000 h • FCvelocity™-HD6 target: 6,000 h • MB Citaro Fuel-CELL: 12,000 h (~ 6 years) • Hydrogen Bus Alliance target (by 2015): 20,000 h	-- • realistic for LFPs: 2,000 – 3,000 <i>c</i> • Ebus: 2,000 <i>c</i> • Altair Nanotech. (HEVs): 12,000 <i>c</i> (~ 15 years) • target for LTO batteries: 25,000 <i>c</i>
Costs	-	--	--
Working as energy storage	Not possible	Not considered	+ (capable of supporting the grid)
Noise level	+(+)	+(+)	++
Exhausts	++	++	++
Carbon footprint * (depends on the production of electricity and APUs)	+ *	-/(+) *, (depends on the H ₂ production methods)	+ *
Passenger comfort	+	+	+
--, Major disadvantage; -, Disadvantage; o, Neutral; +, Advantage; ++, Major advantage (+) a debatable plus; (?) unclear			

5.2.1 *Energy efficiency*

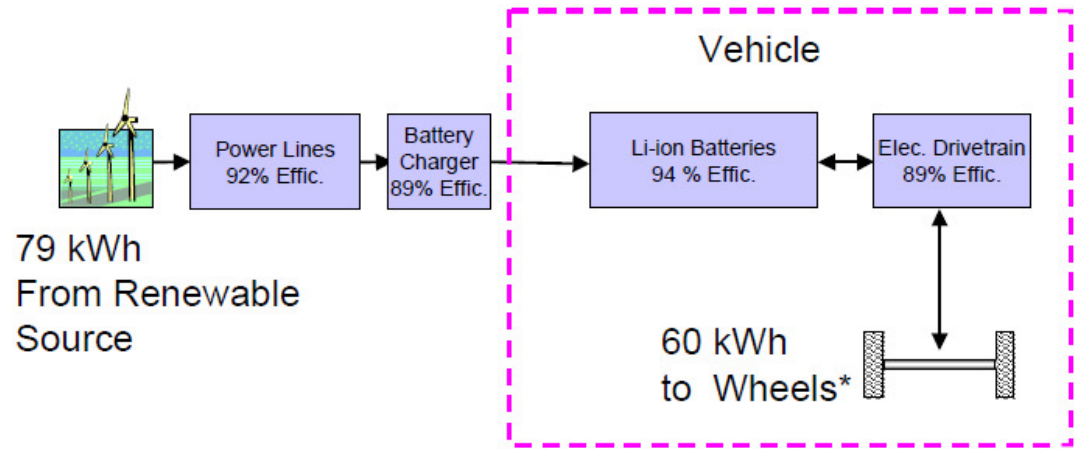
The energy conversion efficiency of an electric vehicle, basically, describes the ratio between the energy provided by the vehicle – used for the vehicle propulsion and auxiliary equipment – and the energy consumed (i.e., in form of fuel or electricity). Overhead lines for trolley buses provide one of the most efficient means of utilising electric energy as propulsion power. Trolley buses do not involve any temporary storage for the used energy. Trolley bus efficiencies were measured within a Canadian study in 2007. The study reviewed a New Flyer-Vossloh Kiepe trolley bus, a model produced in 2006 and utilised in a bus fleet at Edmonton Transit in Edmonton, Canada. The measured efficiencies were evaluated based on power consumption and calculated traction power. Traction power was produced with an average efficiency of 81 percent. Considering the voltage losses in transformers and lines to the trolley bus, the average electrical supply efficiency reached 69 percent. [92]

In contrast to trolley buses, fuel cell buses and battery-electric buses first need to store the electric energy into a specific medium before utilising it in vehicle propulsion. The overall efficiency of a battery-electric vehicle – considering the losses of the electric drive train and vehicle batteries – can reach up to approximately 80 percent [93].

In a study conducted by IFEU (The Institute for Energy and Environmental Research) in 2009, the round-trip efficiencies – the charge-discharge cycle – of Li-ion vehicle batteries turned out to be around 82 – 85 percent [91]. Another study suggests round-trip efficiencies of approximately 70 – 90 percent for an LMO Li-ion battery pack depending on the age and duty cycle of the battery [94]. In the measurements of the European Batteries Ltd., LFP batteries have presented high efficiencies of up to 96 percent when charging with half nominal current [93].

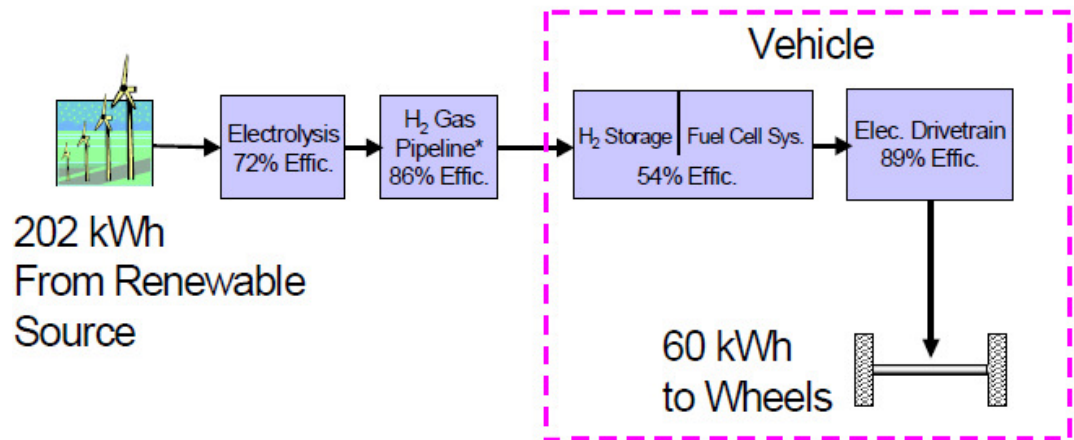
The well-to-wheel efficiencies of different vehicle propulsion types depend on various factors. The production and distribution of vehicle fuel or electricity, as well as the vehicle and related equipment assess the efficiency characteristics of the energy pathway. A United States-based company, Eaves Devices, has published a report (2003) discussing the efficiencies of FCVs and BEVs. In the study, vehicle batteries were compared with fuel cells in order to find the most economical vehicle technology. *Figure 12* and *Figure 13* illustrate the well-to-wheel energy pathways of BEVs and FCVs, respectively. It is noteworthy that the study assumed the hydrogen production to base on electrolysis. Moreover, the production of primary electricity is considered to be produced from renewable energy sources. The well-to-wheel efficiency of a BEV utilising Li-ion batteries came close to 77 percent, whereas the well-to-wheel efficiency of an FCV approximated 30 percent. [95]

For the BEV, Eaves Devices assumed a charger efficiency of 89 percent, a Li-ion battery round-trip efficiency of 94 percent and an electric drive train efficiency of 89 percent. The fuel cell system – including the storage – was assumed to have an efficiency of 54 percent. The common PEMFC efficiency typically stays under 60 percent, as stated in Chapter 3. However, the efficiencies presented in *Figure 12* and *Figure 13* can be seen as suggestive approximations. [95]



*The BEV regeneration capability reduces the 60kWh requirement by 6kWh while achieving the same range

Figure 12: Well-to-wheel energy pathway for BEV [95]



* "Pipeline" includes losses from compression, expansion, storage and distribution

Figure 13: Well-to-wheel energy pathway for FCV [95]

Considering the braking energy recuperation, batteries provide higher efficiencies than fuel cells. According to the IFEU study, the process of storing regenerative braking energy back to the vehicle batteries, and then releasing it for propulsion again, can attain

an overall efficiency of approximately 70 percent. In comparison to the recuperation efficiencies of BEBs, hydrogen generation and transformation from recuperated braking energy to electric traction power only reaches an overall efficiency of 20 to 25 percent in FCVs. In reality, however, fuel cell vehicles often involve some sort of batteries for energy storage, thus enabling better regeneration efficiencies. In trolley buses, the braking energy recuperation is typically either implemented with batteries or the recuperated energy is fed back into the power grid. [91]

While hydrogen technologies do not reach as high efficiencies as what is offered by battery-electric vehicles and trolley buses, fuel cell buses still offer competitive tank-to-wheel efficiencies compared to diesel buses. *Figure 14* illustrates measured differences in efficiencies between fuel cell buses and diesel buses.

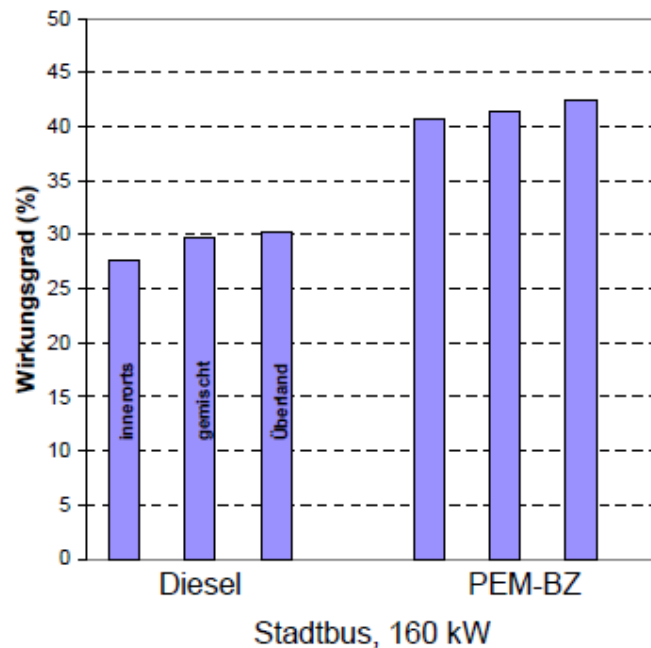


Figure 14: A comparison of PEM fuel cell (Ger., PEM-BZ) and diesel ICE efficiencies (Ger., Wirkungsgrad) in 160-kW city buses (columns from the left hand side: inner city, mixed traffic, city surroundings) [91]

In the IFEU research, the tank-to-wheel efficiency of a fuel cell bus reached up to over 40 percent, whereas typical diesel bus efficiencies mainly stayed below 30 percent. The examination also showed that the efficiencies did not alter drastically whether driving inside or outside the city area. [91]

5.2.2 *Running time energy consumption*

A conventional diesel bus runs 100 km on 45 – 50 litres of diesel. One litre of diesel contains around 36.4 MJ of energy which equals circa 10 kWh. Thus, a diesel bus consumes around 4.5 – 5.0 kWh of energy per kilometre. According to the Helsinki feasibility study on trolley buses, a suitable, comparable figure for trolley buses would approximate 2.5 kWh/km. However, trolley buses in Landskrona, Sweden, recorded an even lower energy consumption level of 1.8 kWh/km with 16 percent of recuperation of braking power during their first service year in 2004 [5]. [3] [96]

Fuel cell buses in the STEP and ECTOS programmes consumed approximately 5.9 and 6.4 kWh/km, respectively. The figures are calculated regarding the vehicle mileage (258,000/90,000 kilometres) and total hydrogen fuel consumption (46.0/17.3 tonnes). In the United States, three fuel bus demonstration sites – i.e., VTA, SunLine and AC Transit – averaged 6.15 miles per DGE, which implies an approximate energy consumption of 3.9 kWh/km. SunLine and AC Transit ran buses which deployed a hybrid propulsion system with batteries enabling energy recuperation during braking. VTA buses attained less encouraging fuel economies under the level of diesel average buses on the site. [14] [54]

The energy demand of an electric traction motor of a battery-electric bus amounts to 1.1 – 1.2 kWh/km. The recuperation of braking energy could reduce the consumption to 1.0 kWh/km. These figures, however, only include the operation of the electric motor; other power electronics involved raise the vehicle energy demand. Table 4 summarises the energy consumption of the discussed vehicle technologies. [97]

Table 4: Tank-to-wheel energy consumption of 12-metre buses

Bus technology	Tank-to-wheel energy consumption*, kWh/km	* per person on average (Helsinki), kWh/km/person	Sources of information
Diesel	4.5 – 5.0	0.38 – 0.42	[3] [96]
Trolley	1.8 (energy recuperation); 2.5	0.15; 0.21	[5] [3]
Fuel cell (Sites in the US; ECTOS/STEP)	3.9 (energy recuperation); 6.4	0.33; 0.53	[23] [14] [29]
Battery-electric	1.1 – 1.2 (pure electric motor demand)	0.09 – 0.10	[97]

Table 4 also suggests the approximate tank-to-wheel energy consumptions per passenger-kilometre. The approximations are based on the average passenger count of 12 persons for 12-metre buses in the Helsinki city public transport calculated later in Chapter 6.2. Albeit the approximated figures are suggestive, they give a clear view of the energy consumption levels. Noteworthy is that the Helsinki feasibility study on trolley buses suggests an energy consumption level of 0.2 kWh/km per passenger, which nearly equals the approximation presented in Table 4 (i.e., 0.21 kWh/km).[3]

Finally, the amount of energy demanded by a bus depends on the vehicle weight, traction type, road profile and other related issues. Suggestive figures help to understand the major energy consumption trends between separate vehicle technologies.

5.2.3 *Other technological characteristics*

In addition to the efficiencies and consumption levels, there are several other factors defining the adequacy or feasibility of a vehicle propulsion type. For instance, all vehicle types differ from each other from the perspective of energy storing. Trolley buses are the only option that does not involve any particular fuel storage. Hydrogen technology makes it possible to produce small-size, high-capacity fuel storages. Hydrogen enables from 2 to 5 times smaller, lighter energy storages compared to any manufactured vehicle battery technologies [91].

Unlike conventional diesel buses, several of the new alternatives have problems with range. Fuel cell buses compete reasonably well with diesel buses since they possess the opportunity to store a large quantity of hydrogen fuel into their tanks. By contrast, battery-electric buses still confront major challenges with the range. Trolley buses, for one, are restricted to routes equipped with overhead lines. According to HSL (Helsinki Regional Transport Authority), the minimum range for a transit bus required in the regional transport in the Helsinki metropolitan exceeds 300 kilometres [96]. This is concluded from the experiences with CNG buses that offered an approximate range of 300 kilometres and required refuelling during the service day. For adequate operation, transit buses should only require refuelling once a day (i.e., not during service). For now a 300-kilometre range is not a possible target for BEBs. However, trolley buses and FCBs are more likely to provide such distances.

An investment to a certain vehicle type sets a question about the expected service life of that vehicle. The winner in this category is clearly the trolley bus which offers a longer life cycle than what is expected from diesel-powered buses (i.e., around 15 years). Trolley buses offer from 16 to 20 years of healthy service life. In contrast to trolley buses, the propulsion poses a difficulty in FCBs and BEBs. A reasonable approximation for an FCB life cycle is currently 5,000 service hours without any repairs done to the fuel cell.

Considering BEBs, LFP battery technologies realistically provide 2,000 – 3,000 deep charge-discharge cycles. Table 3 presents the life cycles provided by the different vehicle propulsion types in form of present facts and future estimations. The maximum vehicle mileage made possible by each propulsion technology depends on various factors and would certainly need more in-depth examination for a reliable comparison.

The suitability of a vehicle type to local transport is also influenced by the demanded infrastructure. Trolley buses require overhead lines on roads and depots. BEVs necessitate a battery-swapping station or a place for recharging the batteries. Trolley buses and battery systems would benefit from the existing power grid. Still, the use of electricity for vehicles' needs could easily create a need for electricity network reinforcing. For instance, possible fast-charging stations for heavy-duty vehicles could overload the electricity network when badly situated. However, fast-charging stations would probably be best implemented when situated on an upper voltage level, closer to the primary substation. Positive is that battery-electric systems could support the national electricity grid, and thus, partially decrease the need for grid reinforcements. Battery storage for heavy-duty vehicles could comprise a greater amount of batteries than what is needed for vehicles providing continuous support to the power grid.

The use of hydrogen would set challenges for the transport system as well. Fuel cell buses involve hydrogen delivery and dispensing systems, comparable to arrangements in diesel and gasoline delivery and distribution. Additionally, fuel cell technology requires special indoor safety systems for leak detection. Small-scale, distributed production and delivery of hydrogen are currently developed in order to provide more efficiency than what is now seen with common petroleum products. The overall economical and technological profitability of a certain vehicle-specific infrastructure depends on the characteristics of the traffic system, as well as the dominating commercial conditions – i.e., the availability and price of the technology. The viability and cost-effectiveness of different vehicle type-related infrastructures cannot be compared to diesel or gasoline delivery chains offhand. On the contrary, the rationality of every system should be considered in itself.

On the vehicle-level, trolley buses – being continuously used for longer periods of time now – are offered through more straightforward manufacturing processes, whereas the production of BEVs and FCVs is still characterised by inconsistency and discrepancy. The availability of FCVs is rather low [91], which is the case for BEV propulsion systems as well. Currently, the immature, inadequate state of development of BEV and FCV technologies restrains cost reductions from occurring. Therefore, the present purchase and maintenance costs for these vehicle types remain high.

5.2.4 *Purchase costs*

The initial purchase costs of different bus technologies vary greatly. Table 5 gives a view of the price differences. Prices in the table represent the price level at the time the vehicle went on sale. It must be noted that the prices for BEBs are not comparable to other full-size bus modes because of the lack of proper information about vehicle prices. Moreover, Table 5 only outlines the overall price levels and gives an idea of the bus market. Excluding diesel buses and trolley buses, prices are gathered from various demonstration projects. Typically, with new technologies, the varying vehicle production methods and market objectives, as well as the lack of wide-scale production widens the price spread.

Table 5: Purchase costs of different bus technologies

Bus technology	Price (1,000 €)	Date of pricing	Source of information, respectively
Diesel bus	250 – 350; 218	2009; 2006	[3]; [49]
Trolley bus	450 – 750	2009	[3]
Fuel cell bus	1,400; 1,200; 805 – 2,410; 1,250	2007; 2006; ~2005; ~2003	[98]; [49]; [50]; [48]
Battery-electric bus/ hybrid-electric bus	204 (small-size battery-electric bus); 383 (hybrid electric)	2008; 2009	[71]; [80]

During the past years, the demand for trolley buses has risen and vehicle prices in Central Europe have reduced over 10 percent. Despite the favourable development of vehicles prices, trolley buses still involve approximately 30 percent excess purchase costs to competing diesel buses. The longer lifetime of a trolley bus slightly compensates the initially higher cost. In Table 5, the price spread of trolley buses is rather wide; the price depends on the passenger capacity and the amount of vehicle articulations. [2] [3]

According to various information sources, the lack of series production and the nature of the fuel cell technology used in separate demonstration projects have kept fuel cell bus prices high. The prices of fuel cell buses have typically been several times higher than for average diesel buses, independent of the geographical location where the bus was used. The latest, large fuel cell bus implementation in the 2010 Winter Olympic Games in Whistler, Canada, incurred initial expenses of around CAD 2.1 million (\approx EUR 1.4 million) per vehicle [47]. An average Canadian diesel bus cost around four times less. [49] [48] [50] [98]

For full-size battery-electric buses, purchase costs are practically unavailable. It is very difficult to obtain any accurate price information since there has hardly been any production of full-size BEBs to date. The initial cost of a battery-electric bus depends on the vehicle and battery size, battery technology, vehicle range, possible APUs used, etc.

The total investment in different electric vehicle technologies in a longer period of time depends on the average service life of each vehicle technology. As presented earlier, battery-electric and fuel cell vehicles still provide rather short life cycles compared to trolley buses. The vehicle technology-related life cycles should be examined more accurately to see how they influence the cumulative costs.

5.2.5 Emissions and consequential impacts on environment

Buses whose propulsion at some point utilises electricity – i.e., trolley buses, fuel cell buses and battery-electric buses – can either decrease or even increase the amount of traffic-related greenhouse gases depending on the nature of the electricity production method. Reducing carbon dioxide emissions is considered important in the traffic sector today. Present CO₂ emission levels generated in Finnish electricity production are presented in *Figure 15*.

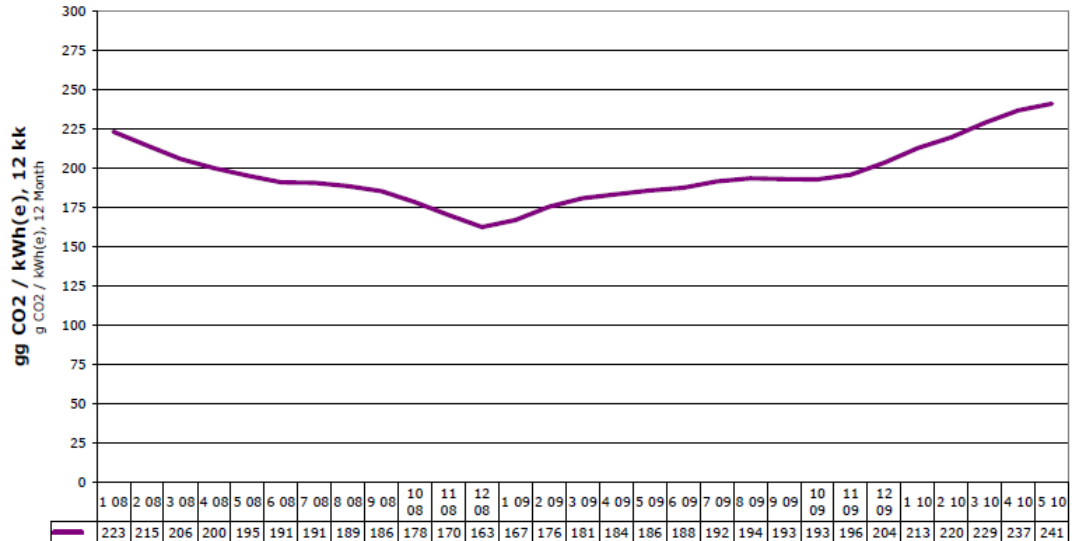


Figure 15: CO₂ emissions (g/kWh) from Finnish electricity production (Jan 2008 – May 2010), 12-month floating average [99]

The VTT Technical Research Centre of Finland has measured emissions generated by various propulsion technologies and vehicle fuels utilised in buses. In 2009, a diesel EEV (Enhanced Environmentally friendly Vehicle) – currently the most advanced diesel

technology on the vehicle market – accounted for the following emissions in the Braunschweig city driving cycle: NO_x, 5.9 g/km; PM, 0.06 g/km; CO₂, 1120 g/km [100]. Table 6 presents Euro VI emission standard and emissions generated by a couple of other vehicle technologies in relation to diesel EEV. The measured PM and NO_x emissions represent exhausts emitted in traffic.

Table 6: A comparison of vehicle emissions generated by various vehicle technologies [100]

Percentage (%)	Diesel EEV	Euro VI (heavy-duty vehicles [101])	Hybrid-electric diesel bus (US)	Trolley bus
Emission				
NO _x	100	20	70	0
PM	100	50	10	0
CO ₂	100	100	70	35; 66 [99]

To assess the CO₂ generation of a vehicle that primarily consumes electricity, the characteristics of the electricity production matter the most. The figures in Table 6 are based on an electricity mix which contains 59 percent of renewable electricity sources along with 22 percent of nuclear power and 19 percent of electricity from fossil fuels. The specific emissions for the used electricity mix total CO₂ emissions of 103 g/kWh which equals the emissions generated by the production of the electricity sold by Nord Pool, the single financial energy market for Denmark, Finland, Norway and Sweden. Carbon dioxide emissions of a trolley bus reach barely over one third of that of diesel EEV – approximately 390 g/km. [100]

If the carbon dioxide emissions from Finnish electricity production (*Figure 15*) were used for calculating the impact of trolley buses in Table 6, and assuming the same vehicle energy demand, the amount of trolley bus emissions would rise to nearly double. Trolley buses would generate approximately 66 percent of the amount of emissions generated by diesel EEV, which implies a figure of over 730 g/km.

Table 6 also shows that trolley buses do not bring in any exhaust-pipe emissions. Battery-electric buses are to large extent similar to trolley buses when considering generated emissions and exhausts. For these vehicle types, electricity production defines the overall emission levels. Presently, one of the major aims stated by policy makers and industry representatives is to reduce exhaust levels along with carbon dioxide emissions. All the discussed alternative vehicle technologies contribute to these aims.

Since fuel cell buses typically utilise hydrogen for the production of electricity to electric propulsion motors, they generate only water vapour and heat as output. Therefore, analysing hydrogen production would make a sensible contribution to getting a view of hydrogen fuel cell-related carbon dioxide emissions. Earlier, in Chapter 3, the CO₂ produced in hydrogen production was defined for various production methods. The emissions from basic, non-sustainable production methods totalled from 12 to 19 kg CO₂/kg H₂. The discussed fuel cell bus demonstration sites in the United States presented an average fuel economy of 6.15 miles per DGE. Thus, the average consumption of hydrogen per kilometre for these vehicles approximates 116 grammes [54]. Considering the CO₂ emission levels from hydrogen production, these particular fuel cell buses would total hydrogen production-based emissions of around 1,400 – 2,200 g CO₂/km which is clearly more than the measured diesel EEV emissions. Again, these emission levels do not involve any carbon capture methods in hydrogen production.

Hydrogen production can be much more environmentally friendly when utilising sustainable hydrogen production methods. An IEA study from 1999 reveals the huge difference in carbon dioxide emissions depending on the nature of hydrogen production. In 1999, diesel was said to generate well-to-wheel CO₂ emissions from 52 to 74 percent of the amount of emissions from gasoline. In the same comparison, total CO₂ emissions from hydrogen infrastructure ranged from 5 to 362 percent (i.e., compared to gasoline), the amount of emissions depending largely on the hydrogen production method and primary energy used for production. Thus, sustainable hydrogen production methods would clearly be beneficial for hydrogen's status among other vehicle fuels in terms of generated greenhouse gases. [102]

The efficiency of the most prevalent hydrogen production technology – hydrocarbon steam reforming – ranges from 65 to 75 percent, one of the highest efficiency rates considering current commercially available methods of production [103]. Close to 95 percent of the existing hydrogen refineries are based on hydrocarbon steam reforming. However, one tonne of refined hydrogen will create around 9 – 12 tonnes of carbon dioxide emissions as a by-product. Therefore, possible methods of carbon sequestration (i.e., carbon capture, transport and disposal) are intensively examined. These methods are still costly, as well as rarely implemented. Sequestration costs are estimated to approximate USD 20 - 100 per tonne of sequestered carbon [104]. For small-scale production, carbon capture is not likely to be a feasible solution [18]. [105]

5.2.6 *Passenger comfort*

Comparing different vehicle types by technical features, related infrastructure and costs, as well as environmental impacts covers a wide range of the necessary study. However, one of the most important factors is missing, and that is the passenger using the vehicle.

Conventional diesel vehicles produce a great amount of exhausts that deteriorate the healthy cityscape. Diesel-powered vehicles are typically generating high noise levels as well.

Trolley buses, fuel cell buses and battery-electric buses are favouring the passenger since they generate less or zero detrimental exhausts. They are also equipped with electric motors which clearly bring down the vehicle noise levels. Trolley buses and FCBs may utilise APUs for additional propulsion power, which may involve increased noise levels. However, compared to diesel buses, all these vehicle types provide smoother, less bumpy rides and a healthier, less stressing travelling environment.

6 Definitions of Helsinki area policies

6.1 HSL

Helsinki Regional Transport Authority (HSL), established on 1st January 2010, is responsible for the planning and organisation of public transport within the Helsinki metropolitan area. The joint local authority currently comprises six member municipalities: Helsinki, Espoo, Vantaa, Kauniainen, Kerava and Kirkkonummi. The organisation that is yet to be joined by several other municipalities in the Helsinki region carries on with the work done by two different organisations before. HSL answers for improving operating conditions for public transport, service procurements for bus, tram, metro, ferry and commuter train traffic, as well as the drafting of the Helsinki Region Transport System Plan. One of the duties of HSL is acquiring or chartering buses for the Helsinki region traffic. Moreover, the organisation is responsible for public transport-related marketing, as well as passenger information and ticket inspection. [106]

6.2 Charter bus fleet characteristics in the Helsinki region – emissions

The morning traffic in Helsinki city comprised altogether 491 buses in the beginning of 2009. The buses which were mostly of the low-floor type were on weighted average 6.3 years old. In calculations concerning the average age of equipment, peak time buses carry five times less weight than other buses. This evens out the associated statistical distortion, the imbalance between less frequently used peak time buses and vehicles with higher mileage. A bus should be replaced not later than at the age of 16 years. Currently, the annual need for new buses is close to 200 vehicles. HSL's bus fleets hold roughly 1,450 buses in total. [107] [96]

The degree of use of public transport assesses the levels of emissions produced per passenger-kilometre and actual, driven kilometres. In 2009, the total mileage of Helsinki city charter buses reached 32.64 million kilometres. 391.3 million passenger-kilometres were recorded on the same stretch of time, which implies an average passenger count of around 12. [107]

The actual amount of emissions generated by the bus traffic depends highly on the vehicle technology. A common way to divide technologies into groups is to classify them regarding the emission levels they generate. The European Union has adopted the European emission standards for heavy-duty diesel vehicle engines (see Appendix A: European emission standards). Table 7 divides the Helsinki city charter bus traffic by emission standards, hence casting light on the rate of use of various bus technologies.

Table 7: Chartered bus traffic by emission rates (Helsinki) [107]

Emission standard	Bus mileage (million km/year)	Share of total mileage (%)
Euro I	0.17	1
Euro II	10.75	33
Euro III	10.26	31
Euro IV	3.34	10
Euro V	0.79	2
EEV	5.20	16
EX-gas-CNG	2.12	6

The acquisition of new buses is restricted to vehicles fulfilling the requirements of at least the Euro V emission standard. A voluntary, additional emission class EEV presents even lower emission rates. Even though EEV buses total 16 percent of the total mileage in the Helsinki bus traffic, one third of mileage still consists of journeys driven by Euro II buses with much higher emission levels. Anyhow, the trend is to minimise the exhaust gases produced by public transport. For instance, a modern system for following the fuel consumption of a certain vehicle or driver has been promoted and should come into play during 2010. In around 2012 – 2013, all buses below the requirements of the Euro III standard in Helsinki should be withdrawn from circulation because of the normal aging of the vehicles [108]. [107]

Table 8 presents the average emission levels occurred from the Helsinki city bus traffic. The VTT Technical Research Centre of Finland has measured the emission rates of different motor types by utilising the Braunschweig cycle. Figures are calculated based on driven kilometres.

Table 8: Average city bus emissions (Helsinki, 2009) [107]

Emissions	Tonnes	g/passenger-kilometre	g/driven kilometre
CO	42.06	0.107	1.283
HC	8.66	0.022	0.264
NO _x	318.01	0.813	9.747
PM	5.03	0.013	0.156
CO ₂	39,428	100.76	1,207.95

6.3 Assessment of transport operators and their vehicles – general remarks

Transport operators for charter bus traffic in the Helsinki city region are commonly chosen through an open bidding competition. Tenders are reviewed carefully by estimating their overall cost-effectiveness. The overall price and equipment quality comprise the most relevant factors in the comparison of new buses. The price of a vehicle is weighted in relation to the cheapest tender addressed to the transport authority. The vehicle is then granted a certain amount of points that eventually determine the most suitable transport operator and vehicle for a certain bus route. [109]

Equipment quality involves various technical features and physical measures. Fully low-floor buses are valued higher than the ones with partly low floors. It is obligatory for new vehicles to have some kind of a low-floor solution [110]. NO_x and PM emissions are rated through the Euro standards. The smaller the amount of emissions, the higher the points for the vehicle examined. Maximum points are given for the motors fulfilling the EEV standards. The vehicle is rewarded with extra points if the noise generated by the motor and tyres stays at 75 dB(A) or less. [109]

In addition, vehicle seating is considered as a part of the equipment quality. To gain extra points from the interiors, new buses should have seats with a clearance of 710 mm or more. Collapsible chairs with the same minimum clearance are also favoured. To reach the maximum points from the seating, seats should offer 750 mm of clearance. [109]

Proper electrical ancillary equipment improves the quality of a vehicle. The transit authority appreciates ancillary equipment, such as automatic air-conditioning, automatic fire extinguishing and an extra heater for the vehicle idling time. Passenger air condi-

tioning should include filters for fresh air intake and cabin air. The air conditioning system should create a cooling power of 20 kW, and as the Finnish winter is rather cold, the system should possess the option of providing 25 kW of heating power. [109]

Besides the cheap price and equipment quality, it is preferred that bus operators orientate and train bus drivers for their job. Bus drivers should go through an annual training day or half-day. The transit authority (HSL) is prepared to arrange and facilitate a certain amount of training. Otherwise, the transport operator organises the training sessions. [109]

In order to maintain easy, safe conditions for passengers, all acquired vehicles must hold several other characteristics. Effortless boarding and alighting, accessibility for the handicapped and enough space for two perambulators are minimum requirements. Passenger comfort should be improved through firm handrails and handles that provide enough support for the passengers. Bus doors should be equipped with safety mechanisms and the vehicle should have safety brakes that prevent the bus from moving while the doors are opened. Clear identification, decent indoor lighting and lighting on bus stops, as well as information material to be provided to passengers contribute to convenient travelling. [110]

6.4 *Carbon dioxide as a decisive measure*

Prior to the new trend for measuring and assessing emission reductions, carbon dioxide emissions were not directly regarded as a pollutive substance. They were not considered in specifying the cleanliness of vehicles for public transport. Now, however, HSL is beginning to emphasise the relevancy of CO₂ emission reductions after a number of studies and general opinions about the effect of greenhouse gases on global warming. [96]

In the future, up to one third of the points granted for the equipment quality in the comparison process of new vehicles could be based on the generated CO₂ levels. Emphasising the role of CO₂ lessens the significance of other emissions and bus characteristics. For instance, the meaningfulness of proper seating and low levels of NO_x and PM emissions will decline to some degree. [96]

HSL is ready to make investments in cleaner, environmentally friendly transport solutions. The transport authority is willing to increase the contract time of new vehicles from the present five years to seven years in the future [96]. This kind of development could realistically lead to more intelligent, innovative vehicle solutions servicing the needs of HSL.

6.5 *Trolley bus as an alternative*

It is clearly evident that the demand for more environmentally friendly public transport is increasing. One of the realistic alternatives for average diesel buses is the implementation of a trolley bus system as a part of the Helsinki region transport. Calculations have shown that a fleet of around 60 – 120 vehicles would provide an economically sensible scale of implementation. [111]

HSL has already planned a possible trolley bus system with a rather large operating area in the Helsinki region. The system would first include 30 vehicles, which would put the system to the test. After a successful beginning, more trolley buses would be acquired. The first phase would entail three bus lines, expanding to 9 bus lines and around 80 kilometres of trolley bus routes in the final system. The objective for operating such a system would need the contribution of around 70 vehicles. Figure 16 illustrates the possible trolley bus system in Helsinki.

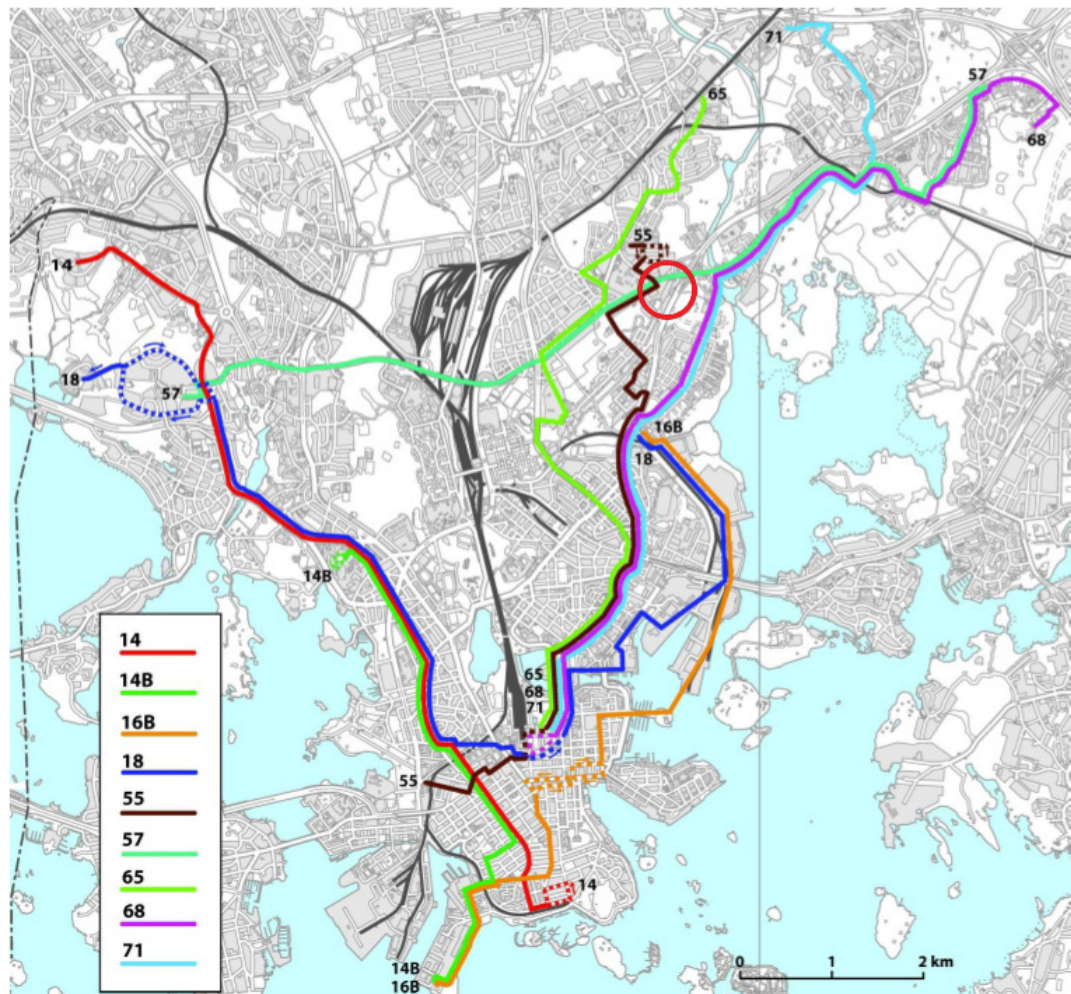


Figure 16: HSL objective for a trolley bus system [111]

Experiences gained from other countries have shown that trolley buses can be conveniently used in parallel with other bus and rail systems. All traffic modes need depots where the vehicles can stay overnight and for maintenance. In Helsinki, the depot of Koskela (red circle in Figure 16) would serve as the main depot for trolley buses. This particular depot holds enough space and a suitable location needed for the implementation of a trolley bus system. [96] [111]

According to HSL, the most suitable alternative for trolley bus traffic in the Helsinki region would involve vehicles with one or two articulations. HSL emphasises the importance of APUs – the deployed trolley buses would most probably carry a 50-kW diesel engine and super capacitors. [96]

One of the major problems with trolley buses is the disturbance to the cityscape. A special commission involving three Finnish cities – Helsinki, Tampere and Turku – has

been concentrating on defining transport systems and solutions that do not disturb the cityscape too much. When implemented, a trolley bus system should incorporate a light overhead line system and other infrastructure in the streets and depots. Diesel generators could be used as the main propulsion provider when driving in the depot. [96]

6.6 *Other modern bus technologies*

In the long run, HSL envisages an increase in the use of electricity within the vehicle industry. Fuel cell buses are technologically available and possible solutions for environmentally friendly public transport but still involve some major difficulties with the price issues and non-conformity. Battery-electric buses and related infrastructure require more development, and thus, are not yet considered as an alternative. HSL is not yet ready to add such vehicles to its fleets.

HSL has sized up fuel cell buses as an option for public transport. However, the expensiveness of the hydrogen fuel makes fuel cell buses an unattractive alternative. Also with the high vehicle purchase price, it would not be beneficial to deploy fuel cell buses in HSL's fleets. The cheapest, and only, tender addressed to HSL for hydrogen fuel has stayed at 9 €/kg (Woikoski Ab). Considering the hydrogen fuel consumption of the FCBs in the ECTOS and CUTE projects (i.e., approximately 0.2 kg/km), the price of each driven kilometre would rise up to an unacceptably high level of 1.8 €/km. Moreover, HSL estimates that the actual hydrogen fuel consumption could even rise up to 0.26 kg/km. [96]

For battery-electric buses, the restrictions mainly consist of poor availability, as well as highly priced batteries and non-standardised infrastructure. In novel vehicle solutions, batteries are typically used for additional propulsion power. The immaturity of the technology and the lack of standards hold back BEBs, and therefore, they are not a short-term option for public transport organised by HSL. [96]

6.7 *Near future environmental goals for Helsinki city traffic*

A working party of the Helsinki city for climate protection has proposed criteria for low-emission vehicles. Objectives of the working party include finding solutions for creating incentives to increase the use of low emission vehicles, as well as establishing a low emission zone to the city centre. [112]

There are several ways for increasing the use of low emission vehicles. Improving the dissemination of information, following experiences gained in other cities and countries, acquiring only low emission vehicles for communal use and promoting additional benefits for low emission vehicles could contribute to the development. In respect to electric vehicles, the city should also define its opportunities to support the expansion of an electricity distribution network. Moreover, Helsinki could make an appeal to the Finnish state for creating tax incentives for low emission vehicles. [112]

For improving the quality of air in the city centre, a special low emission zone is recommended. The special zone would bring restrictions pertaining to the bus traffic and communal waste transport. Thus, it could lead to enhancing the technology used in related vehicles. Emission limits should be created by the transport authorities for communal bus traffic and waste transport – i.e., HSL and Helsinki Region Environmental Services Authority (HSY). Figure 17 illustrates the proposed low emission zone (green), as well as the area currently restricted from vehicles over 12 metres long (orange). The restriction area does not apply to buses. [112]

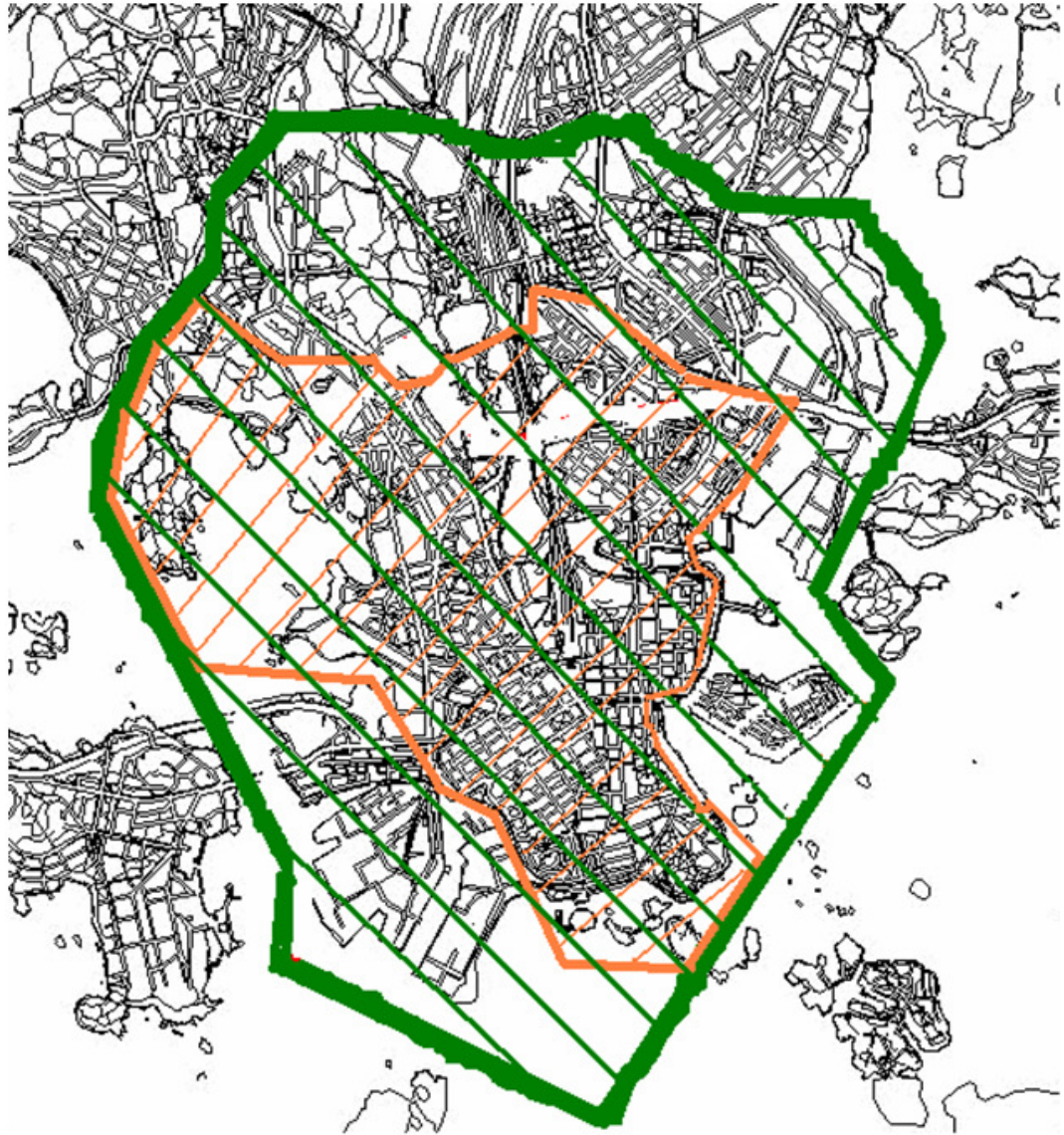


Figure 17: A possible low emission zone for the city centre of Helsinki [112]

In addition to restricting the technology used in public transport and waste management, the low emission zone would be presented and recommended to local companies and communities. [112]

7 Electrification of delivery traffic

7.1 The trend of growing goods transport

Urban environments are full of freight flows heading to various destinations. Not only passengers, but things – e.g., consumer goods, building materials, communal waste, and post – need to be delivered continuously. The nature of the typically unforeseeable delivery traffic differs greatly from the pre-planned passenger transport. The internal structure of average cities does not contribute to the delivery of goods. Freight is often delivered by using inflexible, uneconomical delivery methods and routes. Although the overall delivery of goods lacks sufficiency and efficiency, deliveries must be done in one way or another. [113]

Therefore, efforts made to improve the vehicle technologies used in delivery transport will be highly valuable for the environment. Studies have showed, that freight flows constitute about one fourth of the street traffic of a typical city [113]. The significant amount of goods transport on city roads opens up possibilities for novel, more environmentally friendly propulsion and vehicle technologies. The European Union has set an ambitious goal of decreasing carbon dioxide emissions by 20 percent from the level of 1990 by 2020 [114]. It is a fact that road transport causes 25 percent of all human-based carbon dioxide emissions [115], thus pursuing the goal of the EU necessitates actions not least in the sector of delivery traffic.

7.2 Electrification of delivery traffic – demonstrations and commercial usage

In order to improve the sustainability of local communities, actions for implementing electrification of delivery vehicle fleets have been taken in various countries worldwide. Not every demonstration project of electrification has been successful, but all development and testing of new technologies might be informative benefitting future efforts. The reasonable possibilities for delivery vehicle electrification are mainly provided by battery and fuel cell technologies.

Battery technologies for electric vehicles have faced several difficulties. One of the demonstrations of electric vehicles ending up in a disappointment was arranged in Rotterdam, the Netherlands. In 2001, Rotterdam deployed seven electric delivery vehicles for commercial transport. After several electrical problems with battery management, the operation of vehicles was quit during 2004. The vehicles could not operate efficiently in the daily distribution because of battery system-related breakdowns. The Rotterdam demonstration was carried out in the framework of the project ELCIDIS (Electric vehicles in City Distribution), co-financed by the EU. [116]

However, the continuous development of battery-electric vehicles has made them a real competitor to more conventional vehicle technologies. One of newest collaborations in electric vehicle distribution will happen between the Scandinavian THINK and the French Mobivia Groupe, a company that recently has established a division for sustainable mobility, also referred to as the O2City. The partnership with the Mobivia Groupe provides THINK a great opportunity for large-scale electric vehicle distribution. [117]

The THINK City electric vehicle contains a plug-in electric power train and provides a range of 160 km. Reaching an 80-percent state of charge takes approximately 9.5 hours with slow-charging the vehicle in distribution network (230 V AC, 14 A). Reaching a full charge takes around 13 hours. The batteries used in THINK City involve two different functionalities. Zebra's sodium batteries (MES DEA) operate in temperatures of between 260 °C and 360 °C, while Li-ion batteries from EnerDel provide operation in ambient temperatures. EnerDel batteries make it possible for the vehicle to be unplugged while not in use. The batteries from Zebra provide high energy density maximising the vehicle range. In total, the batteries offer 45 kWh of energy. A rather moderate maximum power of the vehicle power train peaks at 30 kW. The current price for the THINK City electric vehicle in Finland is a little under EUR 50,000 [118]. [117]

THINK and EnerDel have also collaborated before. In 2008, the Japanese postal service went on to start a process of converting its gasoline-fuelled postal truck fleets to battery-electric. The two companies specialised in electric vehicle technologies provided the electric drive system to a Japanese automotive company working under Japan Postal. Conversions were made using the same battery system of EnerDel as in THINK City. The deal was significant since it covered around 5,500 trucks under the operation of the postal service. [119]

The electrification of delivery traffic does not always need to involve small vehicles. Also heavy-duty solutions have been presented for shorter distances within the limits of battery range. An example of heavy-duty electrification comes from Los Angeles (LA), the United States. The port of LA invested in a cooperative project with the South Coast Air Quality Management District in 2007 to demonstrate an electrified heavy-duty truck.

The short-range vehicle was designed by Balqon, a Santa-Ana, California-based developer and manufacturer of heavy-duty electric trucks and tractors. The vehicle is capable of hauling a 40-foot cargo container in full load. The maximum range for the vehicle carrying a full load was stated to be around 48 kilometres. The electric heavy-duty truck is recharged through an existing power system operating at 440 V. Reaching a full state of charge takes around 3 – 4 hours. One hour of charging is enough to provide a state of charge of 60 percent. The LA port reported a clear energy consumption reduction from the earlier 5 kWh_{eq}/km of diesel trucks to 1.25 kWh/km consumed by the battery electric trucks. In 2007, the price of the Balqon heavy-duty vehicle cost circa USD 200,000. [120]

During 2010, Balqon has now established six international dealer agreements after an order for electric drive systems worth USD 490,000 from the China-based DynaProTech in August. The Chinese company has planned to integrate Balqon's electric drive train to electric buses, heavy-duty trucks, light commercial vehicles and passenger cars. DynaProTech will provide Chinese vehicle markets servicing and parts for Balqon's products. [121]

Thus, there is certainly interest towards electrification of various kinds of delivery vehicles. Some electric vehicle manufacturers have reached an economically profitable, solid market base. The industry leader and the world's largest manufacturer of commercial electric vehicles is the United Kingdom-based Smith Electric Vehicles (SEV), a company that produces battery-electric vans and trucks. SEV delivers vehicles ranging from approximately 5.2 to 8.8 metres in length primarily to North America, Europe and South-East Asia. In the United Kingdom only, SEV has a service and support network that maintains over 5,000 vehicles for major fleet operators. [122] [123]

Another means for vehicle electrification is offered by fuel cells. Within the bus industry, fuel cells seemed to incur great costs. The prices of smaller fuel cell vehicles are high as well. However, the technology provides well-functioning solutions already in use. One existing example of utilising fuel cells successfully comes from Toyota's hybrid hydrogen fuel cell vehicle development programme. The FCHV designs by Toyota are based on Toyota Highlander production sport utility vehicle. The FCHV-adv, from 2008, carries a permanent magnet electric motor and a Toyota PEM fuel cell stack both providing a 90-kW maximum output. Additionally, the FCHV-adv is equipped with nickel-metal hydride batteries providing 21 kW. The competitive range of the vehicle comes close to 700 kilometres with the help of two high-pressure, 700-bar hydrogen tanks carrying in total 6.31 kilogrammes of hydrogen. [124]

7.3 *Itella Corporation – delivering postal mail and parcels*

One of the main players to pursue for vehicle electrification in Finland is the Itella Corporation which delivers the daily mail throughout the country. Nearly 17,000 mail carriers and sorters work to ensure the delivery of various kinds of postal items to Finnish households. Around Finland, there are approximately 8,000 letterboxes for smaller mail. Parcels are usually sent from one of the 1,100 Itella post offices. [125]

Itella deploys in total over 5,000 vehicles in mail delivery and logistics services. Combined mileage of these vehicles totals circa 170 million kilometres per year. For mail delivery, Itella deploys around 3,200 motor vehicles. 3,000 of these are vans or cars, whereas the remaining 200 vehicles are smaller mopeds. Excluding mopeds, Itella needs annually from 400 to 700 new motor vehicles for its fleets. Itella typically leases its delivery cars and vans in six-year periods. Currently, the shortest mail delivery route for cars and vans approximates 70 kilometres. The longest routes are around 350 – 400 kilometres long, mostly in Northern Finland. In some cases, the delivery vehicle serving a specific route may have to pick up one or several additional loads of mail from a centralised mail storage point. This increases the daily mileage. [125] [126]

Thus, the operation of the postal service highly depends on motor vehicles. The most efficient way of improving sustainability for Itella is to reduce emissions related to the operation of delivery and logistics vehicles. Besides reducing fuel consumption and carbon dioxide emissions by efficient route planning, combined deliveries and environmentally friendly way of driving, Itella has opted to promote green electricity, vehicle electrification and usage of alternative fuels. [125]

Itella has committed to reduce 10 percent of its carbon dioxide emissions by 2012 and 30 percent by 2030. According to the estimations of Itella, the first goal can be achieved by utilising electric mopeds, but the later aim necessitates other solutions, such as deploying battery-electric vans and cars. The Finnish mail delivery already has experience of electric cars. In the past, the former Finnish mail delivery company, Posti, used over 70 Elcat electric vehicles to deliver mail. Since the poor battery technologies and incompetent range offered by the EVs, these vehicles were not used for long. In 2008, a three-year tryout of Itella, utilising electric Citroen Berlingo, ended after the lead-based batteries reached the end of their life cycle. New batteries would have cost around EUR 10,000 – 15,000. After summing up the pros and cons, the vehicles were not utilised anymore. Currently, Itella has plans to convert a couple of Volkswagen vans to battery-electric. A partner in this project will be the Finnish battery manufacturer European Batteries Ltd. [126]

Itella will also use electric carts, scooters and mopeds. Figure 18 illustrates a Swedish electric moped largely used by Itella in Sweden. This moped type has also been in restricted use in Finland. Itella's plans for the future electric moped fleets include deploying small wind power plants for recharging the mopeds. The wind power plants would probably be located next to the head office in Helsinki. [126]



Figure 18: An electric moped produced by Norsjö Moped AB [127]

Battery-electric cars on the market today offer a driving distance of approximately 150 kilometres. Regarding the energy consuming, cyclical driving profile of the mail delivery (i.e., frequent stopping and accelerating), the range car manufacturers promise, will decrease significantly. This means that the electric cars and vans in mail delivery should be recharged, possibly, several times a day to cover the whole delivery route. Such arrangement necessitates centralised fast-charging solutions.

8 Conclusions

This Master's thesis presented the potential electric vehicle technologies for bus and delivery traffic, particularly to be implemented in the Finnish traffic sector. The study concentrated on vehicle technologies already demonstrated or consistently utilised in regional or local traffic fleets around the world. To get an extensive view of the used technologies, the study described various separate vehicle demonstrations. Two interviews were used to reflect the attitudes towards vehicle electrification in the Helsinki region.

From an economical point of view, an apparently reasonable short-term alternative for the Helsinki region bus traffic is the trolley bus. The city of Helsinki already has some earlier experience of trolley buses from the past decades. Considering the demonstration projects implemented elsewhere, modern trolley buses function well enough in cold climates. The investment price of one vehicle is the cheapest among the discussed bus alternatives. The lifetime of the vehicle also presents a major advantage. One of the difficult issues with trolley buses is the needed infrastructure. A costly, visible overhead network might invoke displeasure.

Fuel cell vehicles and battery-electric vehicles are to be developed further for proper implementation in the future. At the moment, these vehicle technologies are typically either very expensive or provide a short life cycle. The fuel cell and battery technologies are being strongly developed, also subsidised by governments. In Finland, the knowledge of the battery technologies and fuel cells increases all the time. Several state-supported projects aim for the development of these technologies.

Vehicular solutions purely depending on batteries are not seen as a lucrative solution for the bus traffic in the near future. However, demonstrations utilising battery-switching stations or fast-charging points could be used for promoting the future development of vehicle battery technologies, as well as improving the attitudes shown towards battery-electric vehicles. Despite the technological restrictions, batteries might be utilised in buses to provide auxiliary or regenerative power for extending the vehicle range and reducing the amount of generated exhaust gases. In contrast to buses, there are already electric cars on the Finnish automotive market. Thus, it is likely that we will see some kind of electric delivery vehicles or more EVs for car rental soon. The Itella Corporation, for instance, has informed about its interest towards vehicle electrification.

The viability of the different vehicle technologies in public transport or delivery traffic depends highly on the production and costs of consumed fuel or electricity. Hydrogen production and distribution in Finland are clearly not widely enough established to provide a sufficient hydrogen infrastructure for a large-scale vehicular use. The production of hydrogen poses two fundamental problems: high emission levels (i.e., carbon dioxide) and expensive carbon sequestration. These issues hinder the use of hydrogen by making it a very expensive fuel. The Finnish electricity production aims for increased utilisation of renewable energy in order to reduce emissions and hit the emission targets assessed by the EU. The trend of growing renewable electricity production will directly improve the sustainability of battery-electric vehicles and trolley buses.

This thesis discussed electric vehicles capable of utilising external or stored electricity or hydrogen for propulsion. Several electric vehicle technologies were examined one by one to find out the most suitable options for bus and delivery traffic. For more practical results, it is recommended that different combinations of these vehicle technologies (e.g., dual-mode vehicles) and the use of APUs would be examined more thoroughly to find out the most feasible electric vehicle solutions for bus and delivery traffic.

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Appendix A: European emission standards

Table 9 presents the guidelines (i.e., standards) for the maximum emission levels for heavy-duty diesel vehicles inside the European Union. The implementation dates of the standards refer to new type approvals.

Table 9: European emission standards for heavy-duty diesel engines, g/kWh (smoke in m⁻¹) [128]

Tier	Date	CO	HC	NO_x	PM	Smoke
Euro I	1992, < 85 kW	4.5	1.1	8.0	0.612	
	1992, > 85 kW	4.5	1.1	8.0	0.36	
Euro II	Oct. 1996	4.0	1.1	7.0	0.25	
	Oct. 1998	4.0	1.1	7.0	0.15	
Euro III	<i>Oct. 1999, EEVs only</i>	<i>1.5</i>	<i>0.25</i>	<i>2.0</i>	<i>0.02</i>	<i>0.15</i>
	Oct. 2000	2.1	0.66	5.0	0.10 0.13 ^a	0.8
Euro IV	Oct. 2005	1.5	0.46	3.5	0.02	0.5
Euro V	Oct. 2008	1.5	0.46	2.0	0.02	0.5
Euro VI	Jan. 2013	1.5	0.13	0.4	0.01	
^a for engines of less than 0.75 dm ³ swept volume per cylinder and a rated power speed of more than 3,000 min ⁻¹						