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DATA ANALYSIS OF ELECTRICAL ENERGY CONSUMPTION OF ELECTRIC BUSES

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ABSTRACT

Aleksandr Chernykh: Data Analysis of Electrical Energy Consumption of EBuses
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This study analyses the data of electrical energy consumption of eBuses provided from Smart Tampere. The data was collected from 4 eBuses operating in Tampere, Finland during 2017-2018. The importance of electrical energy consumption data collection comes from necessity of understanding the behavior of eBuses in a mid-sized city and comparison of advantages of those to diesel buses.

This work provides the results calculated from provided data and gives the example of necessity and implementation of those for cash flow calculations. The results include, the average electrical energy consumptions of eBuses per hour, per day, per month, per season and per kilometer. The implementation of calculated electrical energy consumption of eBuses per kilometer was applied to previous studies of feasibility of electric buses in public transport to compare calculations with estimated values to those closer to real-time based results.

The results showed the importance of the accuracy of electrical energy data collection, the necessity of future developments in data collection and the effect of accuracy change on cash flow calculations. The results from calculations of cash flows showed, that even the slight change in accuracy of energy consumption results might move the break event point between diesel buses and eBuses up to 1 year further or backwards. The average values of electrical energy consumption calculated in this work appeared to be different from the same values estimated in previous researches up to 0.4 kWh/km. The ways to improve further electrical energy consumption calculations were introduced and explained.

Keywords: thesis, ebuses, electrical energy consumption, electric buses

PREFACE

This thesis work was written based on the data provided from Smart Tampere and previous publication with the topic in Feasibility of electric buses in public transport. The data was provided in January 2019. The publication on Feasibility of electric buses in public transport was published in May 2015 and was written by Olli Vilppo and Joni Markkula.

This study oriented on those, who will be willing to continue to do deeper research on the topics related to electrical energy consumptions of electric buses. This work may serve as the basis for future studies of the data provided from Smart Tampere.

Tampere, 23.9.2019

Aleksandr Chernykh

CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

EBus	Electric Bus (or E-Bus)
EV	Electric Vehicle
BNEF	Bloomberg New Energy Finance
HSL	Helsinki Regional Transport Authority (translated from Finnish)
NPV	Net Present Value

1. INTRODUCTION

The near future trends seem to be changing in terms of the implementation of more and more Electric Vehicles instead of diesel- and gasoline-based transport. The price for the EVs decreases, because the production of necessary systems and engines for it is more accessible and understandable these days, which leads to wider integration of those to the public usage. Together with price, Electric Vehicles help to reduce the noise levels in cities, improve the air quality and decrease the emissions of CO2.

However, at the same time such evolution and change in integration of the higher amount of EVs have a significant impact on the power distribution in general because of the need in charging. Electrification of transportation decentralizes the electricity network, because the generated electricity must be provided to the final customers for charging the Electric Vehicles. Thus, the high interest in the implementation of EVs for reducing the pollution leads to higher electricity demand from the power grids. There are few options on how to reinforce and improve the power networks to be able to provide enough energy for charging the Electric Vehicles, it includes connecting renewable sources and storage technologies. [1]

On top of that, the discussion goes not only for the EVs such as cars, but also for the public transportation, such as Electric Buses or, simply, eBuses. EBuses are the good replacement for the diesel buses in terms of the noise reduction, improving local air quality and decreasing the pollution level of CO2 in cities. Moreover, the amount of charging stations needed for recharging buses is not necessarily big, because for short-route buses it is possible to use chargers located at the final bus stops and charge them within the night for the further use during the next day. Every public electric bus has own route, length of that route, schedule with the specific time, available mileage for the day and time to operate which means, that the optimal strategy for the energy use for the one bus should not be difficult to define. [2]

With all above said, the transportation electrification could be introduced as a way to increase the quality of the air with lowering the CO2 emissions and other local particles, reduction of the noise and, in simple words, as a way to get closer to climate goals. However, to gain all the shown benefits and make EVs easier to implement and distribute, several problems are faced. Among such problems are still high price for the EVs and batteries used in them, the environment for implementing the changes related to Electric Vehicles is raw and not completely ready yet and the effect on the power distribution from the new implementations still holds the future trend back. Although, overcoming the appeared changes will take some time, it is still possible to build the network with integrated Electric Vehicles inside of it.

1.1 Objectives and outline of the thesis

Objectives of this thesis work include analysis of the real data provided from four electrical buses in Tampere, Finland. The data from eBuses includes battery state of charge, conditional power moving, distance, energy consumed, speed etc.

This thesis work is planned to demonstrate calculations of provided data and show the necessity of those for cash flow calculations. Methods used for this will be based on the analysis of data in Microsoft SQL Server Manager, defining the electrical energy consumption of eBuses per kilometer and implementation of it to previous studies of feasibility of electric buses in public transport for comparison.

Another research question followed by this work will be the actual energy consumptions of eBuses during different periods of time. Those include electrical energy consumptions per day, per hour, per month, per season and per kilometer. Methods used for this will be based on sorting out the data via programming codes in Microsoft SQL Server Manager and on basic electrical calculations.

The ways to improve the data and further electrical energy consumption calculations will be also discussed. Such assumptions will be based on faced difficulties in defining the accuracy of every calculated value in this work.

2. BASIC CONCEPTS OF THE EBUSES

Nowadays it is possible to use the advanced battery technologies efficient enough to implement those for the public transport. EBuses are the new option where such technologies could be invented.

Only about 10 years ago from now, the implementation of eBuses instead of traditional diesel buses seemed to be not competitive in terms of economic and technical point of view. The implementation of electric buses was restricted to only small route tests and operations. However, constant researches and development leaded to upgrading from small-distance routes to the possibility of actual change some of the regular route diesel buses to electric buses within the cities. The EV technologies are still improving.

Nevertheless, the change from traditional buses to eBuses is not the only the issue of the technology. There are plenty of challenges facing this transformation of public transportation. Diesel buses are still beating electric buses in the competition of autonomy in some ways. However, electric buses might be a good alternative of a smart city transport system. [3]

There are still several questions to be solved on the path of the implementation of eBuses to the current transportation system. Among those are the price of electric buses, building the charging infrastructure, driving range and time of charge. Nevertheless, the future for electric buses seems to be closer than ever.

2.1 What are the eBuses

Modern eBuses appeared in the market in early 2009. At the beginning, the first versions of such buses had a smaller size (approximately 8-10 meters long). However, such characteristics changed with time, because the newer battery technologies have been improved. Thus, new buses came into the market and now they have a bigger size (about 12 meters long) and work much more efficient than the previous versions. [4]

The concept of the operation of the eBus is the usage of so-called on-board batteries. Thus, the operating power for the bus is used from such battery and used for air-conditioning and heating inside the bus. [5] Figure 1 demonstrates a simple scheme with the elements included in electric buses from Espoo and Helsinki, Finland. It has a battery which is charged automatically for 1.5-3 minutes at bus stops while this bus is being loaded with passengers. Driver controls the bus via controller which is connected to inverter. Inverter is necessary for battery and engine operation.

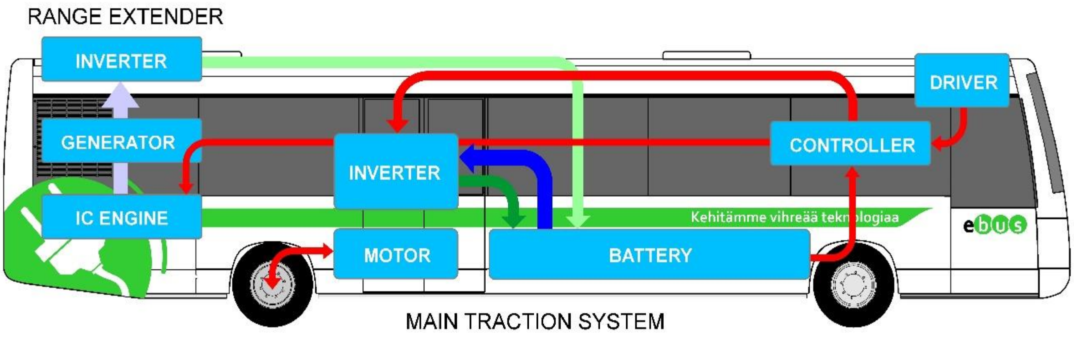

Figure 1. *Fast-charged eBus from Finland scheme [6]*

Charging the eBus battery is more difficult to compare to buses working with combustion engines, because it requires the necessary infrastructure for providing the power to the bus. The other needs come along with the infrastructure, such as proper battery maintenance, continuous monitoring, different scheduling of the bus routes coming from the point that buses should be charged more frequent compare to buses working on diesel or gasoline, it also requires defining the optimal solution for the charging process. Together with all the stated issues, the implementation of the Electric Buses also needs the civil reinforcements in the cities, such as building the power charge stations at the end stops or constructing the bus stops for the fast charges along the way of the public transport routes.

Nowadays, there is also a multiple amount of the software companies working towards developing the programs which allow reschedule the eBuses timelines, recalculate the routes and define the right locations for the bus chargers. All that gives an advantage to operate the Electric Buses safer, hold the right schedule for the bus drivers and ensure that the passengers can get the value and even more from the use of eBuses. [7]

2.2 Types of eBuses

Nowadays there are three types of electric buses in use among all the countries: hybrid electric bus, fuel cell electric bus and battery electric bus. The difference among those is mainly concentrated on generated energy or energy stored in the bus itself. To be more precise on each type [8]:

- Hybrid electric bus - a diesel engine inside of the bus produces electricity during operation.

- Fuel cell electric bus – hydrogen fuel cells produce electricity for the usage while bus is operating.

Battery electric bus – basically, charged in one time or during the road trip. Energy stored and then used while operating. Figure 2 helps with the visual understanding of all three types of electric buses principles.

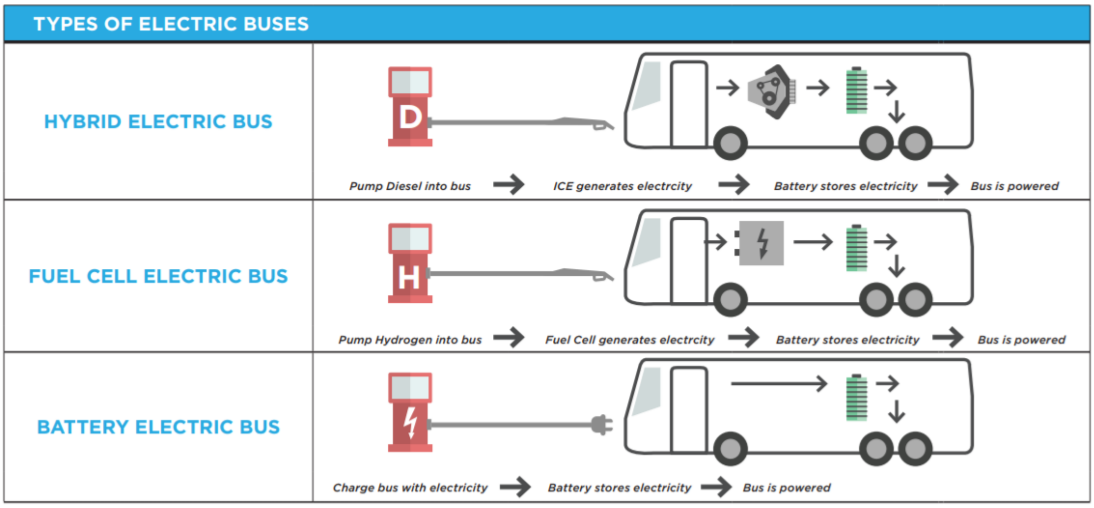

Figure 2. *Main elements of different eBuses types*

Hybrid electric buses working principle is based on both a diesel-powered combustion engine and an electric motor. This type of electric buses is the most common in the world at the present moment. The main advantage of such buses is that there are less changes in technology from traditional diesel buses. The disadvantages include heavier overall weight which leads to restricting the types of roads it could be driven on and lower capacity; higher overall costs due to requirement of two propulsion systems; requirement of changes in charging infrastructure; battery lifecycle can still be affected by the temperature.

Fuel cell electric buses are operating based on chemical reaction between collected hydrogen and ambient oxygen to generate electricity. There are few different types of fuel cells such as, for example, polymer electrolyte membrane fuel cells which are the most common in fuel cells electric vehicles production. The advantages of such type of electric buses are lower CO2 emissions; less need for maintenance due to almost no moving parts needed to generate electricity; long-range driving distances. The disadvantages are the need in changing the infrastructure (it is necessary to have a hydrogen storage and the special equipment for refueling); expensiveness due to the price for buses and necessary infrastructure; very careful management of the bus system is needed due to sensitiveness of components to temperature changes; more storage space needed for the hydrogen, because it is less energy-dense.

The last type is battery electric buses. This type of buses stores all the energy in the integrated battery inside of the bus. The battery is charged while bus is on the charging station and/or recharged on bus stops during the route trip. Regenerative braking can also be used to bring some of the energy back to the battery. The advantages of battery electric buses are very low CO2 emissions; high efficiency; the operating cost is lower compare to traditional diesel buses. The disadvantages of this type are low-range driving distances; heaviness due to still large batteries; lower capacity which is coming from the previous point; necessity for the change of charging infrastructure.

Even though there are few types of electric buses, in this thesis work the main concentration will be focused on battery electric buses. The further research is based on the data from 4 electric buses driving in Tampere, Finland provided from Smart Tampere. [9]

2.3 Advantages of implementing eBuses in the future

Most of the advantages from the implementation of the eBuses are obvious and may be seen easily, such as the decreased level of CO2 and other emissions from local air quality point of view, and noise level reduction. However, there are more than that, if it would be observed from different fields, operators and suppliers. Figure 3 shows what value could be brought from implementing the eBuses for such different points of view.

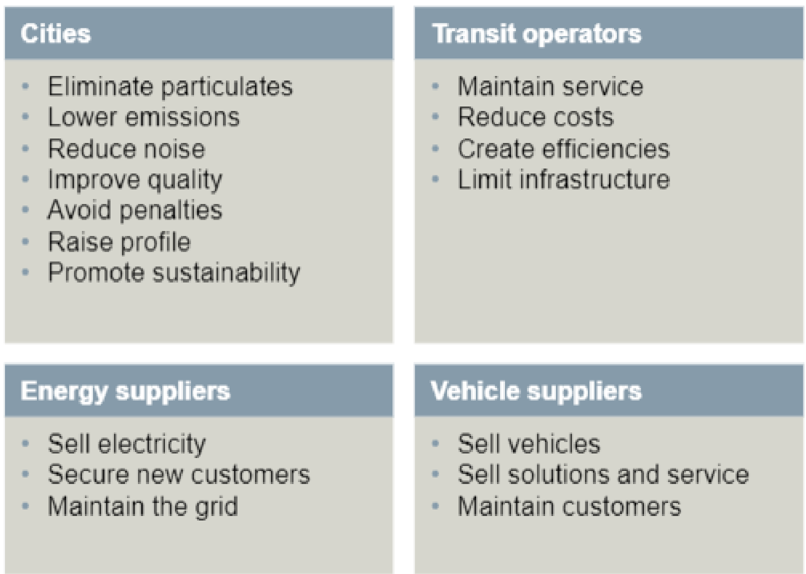

Figure 3. *Value brought from implementing the eBuses for different fields [10]*

Thus, compare to traditional buses, Electric Buses provide advantages for the producers and inventors of the eBuses, because they can mainly benefit from the selling of electric public transport together with the service provided and the continuous maintenance after the deal with the customer. For the energy suppliers it can bring the values in terms of earnings of the electricity and maintaining the existing customers which use the charging technologies. Transit operators also benefit from the integration of the new technology in terms of maintaining the service, reducing costs, creating efficiencies and limiting the infrastructure. Finally, cities can gain the most advantages from the usage of the eBuses. For cities it brings on the table lower CO2 pollutions, the lower noise level, better air quality and the raise the profile of the city in general. The transition from traditional buses to electric buses can also be considered as an advantage for saving more fuel.

2.4 Temporary limitations of the conversion to eBuses

The previous chapter gives an idea of different advantages from the integration of electric buses instead of traditional diesel buses. It is clear, that this change brings much more opportunities for cities, transit operations, energy suppliers and even vehicle suppliers. However, it raises a question about the difficulty of the actual implementation of electric buses. Why there are only few countries which are able to do such change and why this change grows very slow?

The answer to this question is not actually hidden, although the number of factors contributing to the explanation of this is quite large. Some may say, that the advantages of the implementation of electric buses are not necessarily worthy compare to the amount of additional installations it needs. Not only installations, but the prices of electric buses itself are quite high at the current moment.

First of all, the battery which is the main component of any electric vehicle is still very expensive. The main reason to this is that the technology itself is still pricy, and the price of lithium is high. Batteries are the main reason why any electric vehicle is so expensive. The price of only this element can contribute to the cost raise of the EV twice higher. Nevertheless, the prices of batteries are consistently decrease as all the researches in that area are becoming more and more productive.

Secondly, all the electric buses still have limited driving range, compare to traditional buses. This may lead to the necessity of building more charging stations not only at the depots or bus stations, but also along the regular driving routes of buses. Even if provided for the bus battery is in balance in term of price/range-per-charge, most of electric buses can only be applied within the city range. Otherwise, the price of the vehicle dramatically increases with the increase of one-charge range of electric bus battery.

Another problem in integrating more electric buses is the lack of proper charging infrastructure. Not only the implementation of buses, but also other electric vehicles is more difficult because there are yet not enough charging stations among all the countries. If there is a possibility to integrate electric buses in one city with only few depot charging stations, there is still a problem to use the same tactics for buses traveling outside the city. Moreover, because of low-range distances, electric buses may even need in-between charges on regular routes within the city.

Fourthly, even if there would be an ideal charging infrastructure for electric buses, the problem of long charging times still appears. It would be inacceptable for those who travel by electric bus to spend few more hours on the road just because of charging necessity. More on this will be described in the next paragraph.

Thus, the world still faces some difficulties with the conversion from traditional diesel buses to electric buses. It might take few more years to succeed in the research in this area which will lead to better situation related to this change. However, the progress in this field is noticeable and all the difficulties seem to be solvable in the future.

2.5 The charging technology for eBuses

There are two types of the battery charge, that could be used for the eBuses batteries – inductive and conductive. Charging can also be static, stationary or dynamic. Static charging relates mostly to the charging condition of not moving bus which is usually applied for a certain amount of time in the places, such as for instance parking spot in the depot. Stationary charging is also applied for not moving transport, but with this method public transport stays for a shorter amount of time at the charging spot which could be for example a bus stop and charging will happen automatically. The last type is called dynamic charging and means that an electric bus will be charged while it is driven on the route. However, the dynamic charging is still in developing phase, that is why it is not widely used at the current moment.

Conductive charging means, that the energy to the bus battery is transferred from a voltage source via an electric conductor. This is the most common method of charging nowadays. Advantages of choosing such charging option is that it has a high efficiency and has a smaller chance to be damaged compare to inductive charging method. However, it has higher maintenance costs due to the usage of wire between the conductor and the collector while charging.

The principle of inductive charging is that the power is transferred with a magnetic field with the usage of two coils of wires that are located close to each other. AC power flows through one coil and via the magnetic coupling between both coils this power can be extracted to the second coil. This charging method is shown in Figure 4. The transferring of the inductive energy is efficient, but it highly depends on the location between coils relatedly to each other. [11]

The traditional technique of charging the bus is the one which is made overnight at the bus end stops. Another way of charging the bus is called the opportunity charging and represents the fast and intense injection of power at certain points on the route which gives the advantage for the longer-range drives. Figures 5, 6 and 7 demonstrate the different charging methods with the charging times, powers and other related points. [12]

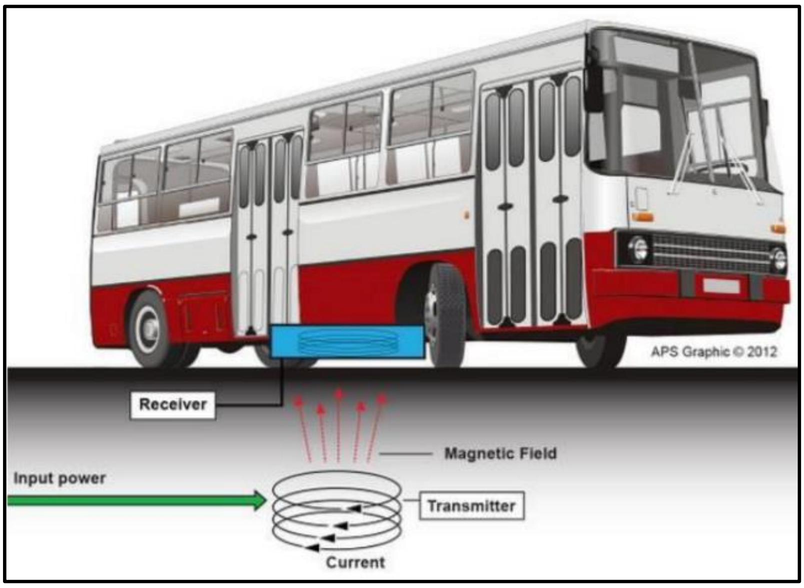

Figure 4. *Inductive charging of the eBus*

Plug based charging AC or DC

- Charging time 2-14 hours
- Charging power 20-50 kW
- AC on-board charge
- DC off-board charging
- Location depot or end-stop

Figure 5. *Plug-based charging solution of the eBus*

Opportunity charging

- Charging time 15 seconds
- Charging power 400 kW/ 200 kW
- Energy storage grid connect 50 kW
- Automated on-board pantograph
- Location each 3-4 stops

Figure 6. *Opportunity charging solution of the eBus*

Figure 7. *Opportunity end-stop charging solution of the eBus*

Analyzing the charging solution introduced in the pictures above, it could be noticed that the plug-based charging for the buses requires a large battery, because the energy density of the battery in such case should have higher rates to give the advantage of driven on the longer-distance routes. That situation could affect the number of the passengers in the bus, in terms of space and weight of the bus itself.

From the observation of the second method which is the opportunity charging, could be more efficient in terms of the problems with the previous method. That method requires a smaller battery, which could be more efficient for the public transportation buses as long as it needs less sacrifices for the space inside of the bus and its weight. However, that way of charging the bus faces another problem such as the requirement in more frequent charges along the driving route. The last point leads to another need for such charging which causes more costs for charging stations, because, as it was stated in the figure, the charging stations should be located at every 3rd or 4th bus stop.

The third solution which is the end-bus-stop opportunity charging, gives an advantage of charging the bus faster, and allows the bus to travel the distance approximately 5-25 kilometers. That way of charging seems to be the best solution for the public transportation buses which are traveling on the city routes.

2.6 Economic performance of eBuses on different traveling ranges

The literature review gives an idea, that eBuses can already be cheaper on the terms of total cost of ownership than traditional diesel buses. [13] Nevertheless, the complete picture consists not only with operational point of view, but also with prices of fuel, maintenance and changing the whole charging infrastructure to make the change available. However, the prediction of the future technology development shows, that soon electric buses will take over traditional diesel buses due to consistent decrease of e-buses total costs.

The comparison of eBuses and diesel buses from the scale of costs per kilometer demonstrates, that with the increase of traveling range costs per kilometer decreases in both cases. However, the breaking point happens on the large city annual mileage where e-buses become having cheaper price per kilometer than traditional diesel buses. Figure 8 illustrates the comparison of electric buses and today's conventional buses with different range of travels per year (the diesel price is considered \$0.66/liter and the price for electricity is \$0.10/kWh).

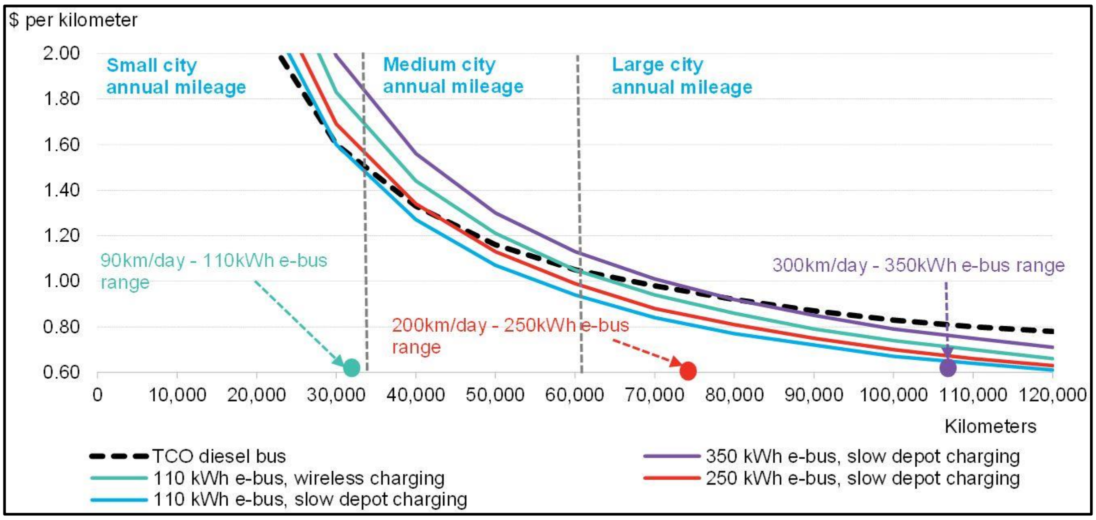

Figure 8. *The comparison of electric buses and today's conventional buses with different range of travels per year [13]*

Thus, different e-buses with various types of charging can be chosen for the integration instead of regular diesel buses where the mileages on routes per year are high. In that case, even electric bus with slow depot charging and 350 kWh battery will be more profitable with the traveling range more than 80 000 kilometers per year in terms of total cost of ownership compare to diesel bus. However, the price for electric bus itself is still higher than for traditional diesel bus and additional costs are also related to changing the charging infrastructure. Nevertheless, all the predictions for the future technology developments illustrate significant decrease of e-buses prices. In 2016 the price of the battery for the electric bus was 26 % of the total price of the bus. By 2030 the price of the battery pack inside e-buses is predicted to decrease to 8 % from the total price of the bus which is a very significant change. [13]

EBuses will still be more expensive than the buses which are working on the diesel or gasoline. However, according to the research of BNEF (Bloomberg New Energy Finance), the total cost related to the Electric Buses will be lower, if the price of the fuel and maintenance of different buses are included in calculation. Moreover, it is predicted, that the price for the batteries will become lower compare to the diesel and gasoline engines by approximately 2025 which means, that the total costs of the new buses will be even more attractive. Thus, more and more eBuses will come into market, because the traditional buses will eventually bring significantly less advantages than Electric Buses. [14]

2.7 Worldwide situation and case studies

Nowadays, there are many countries considering and even already implementing eBuses for the usage. Most of the countries are only testing eBuses and working on the analysis of the data collected from testing. However, China is the leader in the integration of eBuses at the present moment. Moreover, for the purpose of this thesis work it will also be interesting to get more familiar with the current situation in Scandinavian cities, especially Tampere, Finland.

Regulations related to moving automotive industries towards electric vehicles with less emissions also appear in European countries. The largest part of the plan in reducing CO2 emissions and pollutions in the cities are taken for electric transport such as eBuses. The main reason of relying on eBuses in that case is that all the automotive companies should produce more passenger private electric cars compare to electric pubic transport for the cities.

Implementation of electric buses has been increasing in Europe for the past few years. Estimated amount of orders within the 2017 was around 1000 eBuses in European countries. Main supply brands in the usage are: BYD; Solaris; VDL; Volvo; ABB and Siemens. Chinese automaker BYD Auto has a huge production network of electric buses in European countries such as Hungary, France and the UK. There are also few other brands producing eBuses which found implementation of own products within the Europe. [17]

2.7.1 E-buses in China

Approximately 50 % of the traditional buses will be replaced with Electric Buses in the next few years, where, for example, China is expected to be the leader in the global market at that time. [14] Figure 9 shows the prediction of the total eBuses deployments until the 2025 in China.

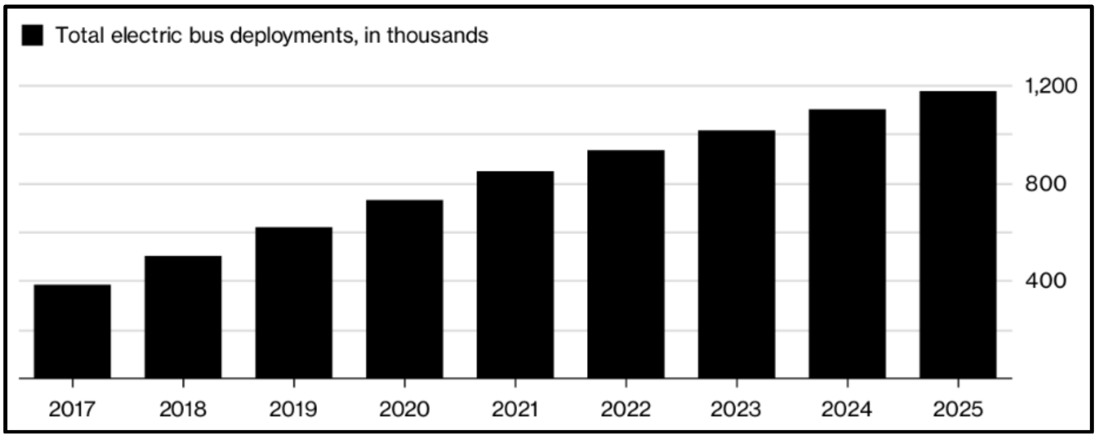

Figure 9. *Total eBuses deployments until the 2025 in China [14]*

Thus, BNEF mentioned, that approximately 400 000 e-buses operated around the world in 2017, most of those belong to China. The interesting prediction is that in less than 7 years from now, electric buses in China will reach the number around 1 200 000 of electric buses which will still be the biggest part compare to the other countries. [18]

China is the leading country in terms of implementation of e-buses which creates the opportunity to grow for the other countries in the world in terms of the usage of electric buses instead of traditional diesel once. If all the predictions will be correct, China will significantly decrease the total level of harmful emissions by 2025.

2.7.2 E-buses in Scandinavia

When looking at the situation in Scandinavia, all the countries slowly come to the integration of more and more electric buses. The whole situation looks in a way, that some routes in few cities are operated fully with Electric Buses, like, for instance, in Helsinki, Turku and Tampere in Finland, Gothenburg in Sweden or Oslo in Norway.

Gothenburg received the order with 30 electric buses in early 2018 which was the biggest order of e-buses among all the Scandinavian countries by that time. The buses are already operating, and the authorities of the city plan to continue growing in terms of reduction of harmful emission in this way. The target is to integrate the amount of electric buses by 2025 which will take 95 % of all transport. [19]

Oslo in Norway received 17 e-buses in the middle of 2018. In total, together with Oslo there are three more cities (i.e. Trondheim, Drammen and Lillehammer) in Norway which made an order for battery electric buses. The country also has a target in increasing the number of electric buses in the future. [19]

To continue the discussion about the electric buses in Finland, the Helsinki Regional Transport Authority (HSL) plans to replace at least the third part of electric buses in the

Helsinki metropolitan area by 2025. [15] Some routes are already taken and operated completely by the Electric Buses.

According to the related integration of the new studies of the buses, the implementation of the eBuses will affect the ticket prices in a positive way. Together with that, the Electric Buses will provide the greater speed and will steadily increase the air quality level in Helsinki, as said by the executive director of the HSL [15]

On 23 January 2017, eBuses supplied by the Electric Buses manufacturer Linkker were launched and started to operate on the line number 23 which is located from Ruskeasuo to the Railway Station Square. [16]

The charging stations for the Electric Buses on the line 23 are located at the Orton Foundation (at the Ruskeasuo end-stop) and at the Railway Station Square. More charging stations are being planned to construct for the possibility to integrate the eBuses for the other routes. The Linkker buses are the Electric Buses with the fast charging. [16]

2.7.3 Tampere case

Another city in Finland which is participating in the integration of electric buses instead of traditional diesel buses is Tampere. At the current moment there are four battery electric buses and two hybrid buses operating in the lane 2 which length is approximately 4.7 kilometers. EBuses were integrated to the route in 2017 and hybrid buses in 2012.

Tampere City Transport managed to collect the data from electric buses for approximately one year. Among all the variables are e-buses speed, energy consumption, charging time, temperature, battery state of charge, battery power, distance, etc. Collecting the data is the part of STARDUST project which supports the target of Tampere authorities to become carbon neutral city by 2030. [9]

The data includes successful measurements of e-buses conditions during different seasons of the year. From the own experience of the author of this work, it is noticeably more comfortable to take a ride on electric bus due to less noise while operating.

Figure 9 shows the route of electric buses on the line 2 in Tampere. The final bus stops on two ending of the line are Rauhaniemi and Pyynikintori. The distance between the final stops is about 4.7 km.

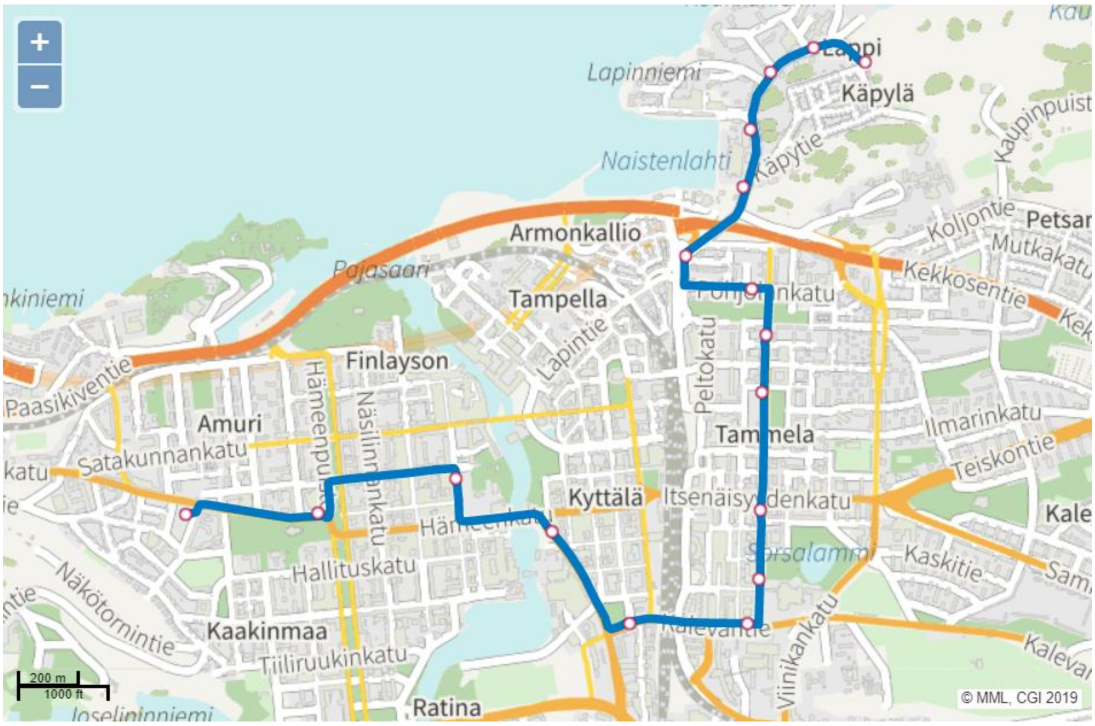

Figure 10. *The route of electric buses on the line 2 in Tampere, Finland*

By the collected real-time data from electric buses in Tampere is a good opportunity to do a research in terms of energy consumption of e-buses. It can give a reliable foundation for discovering various factors affecting the energy consumption calculated in earlier works with only assumption methods for the future development.

3. DATA AND METHODS CONSIDERED IN THIS THESIS WORK

All the data for this work is provided by Smart Tampere. Measurements from Tampere electric buses are collected from 2017, and by now the data has been collected for almost a year.

Many various variables had been recorded in one large database. All the information has been collected from four e-buses driving on the same route in Tampere, Finland. Among all the variables for this thesis work only speed of the vehicle at different time periods, driven kilometers (distance) and the energy consumed during those periods were considered. In the provided data, hourly energy consumption was given for only one bus, the other variables (distance and speed) were taken for every 5 seconds for each of four buses.

In this part of work, the data itself and the methods of managing this data will be discussed. Moreover, the preparation phase will be described to help of any future studies of the same data. Thus, it may be considered as the necessary basics for managing the provided data.

3.1 Microsoft SQL preparation for opening the data

The received data is in BACPAC file type. BACPAC file is, basically, a ZIP file which contains the data from a SQL Server database. Thus, to open this type of file the SQL server installation is needed. All the necessary tools could be downloaded from the official Microsoft webpage.

First, the server installation is required for the SQL server management tool to be able to refer to that particular server when extracting the data from the BACPAC file. Server was installed to the same PC, where the actual file was located.

Secondly, to operate with the server, the software is needed. SQL Server Management Studio (SSMS) was downloaded from the same Microsoft official webpage. After the installation, the connection was required to start working with the server.

After the connection, the data was uploaded to the server. The process took approximately 6 hours. Figure 11 demonstrates the result after uploading the BACPAC file to the server with all the tables names containing the collected data.

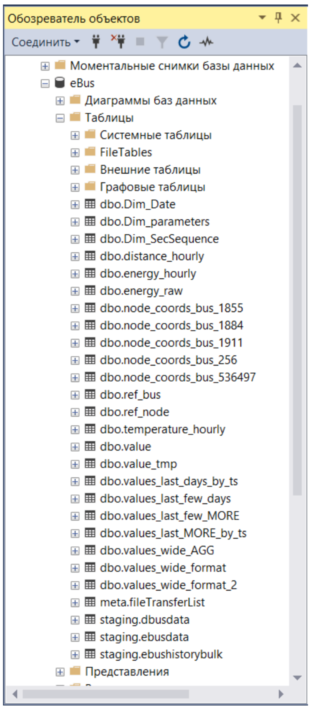

Figure 11. *Opened BACPAC file on the SQL Server with all the data separated in tables*

After that, it became possible to use the inside SQL language to operate with the data. Each table consists of own original variables. Figure 12 provided from Smart Tampere helps with the decoding of all the values provided for four electric buses.

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		256	1855	1884	1911		
	A	B	C	D	E	F	G
1	attribute	Datanode bus 1	Datanode bus 2	Datanode bus 3	Datanode bus 4	Unit	selite
2	air temperature	479	2070	2091	1921	°C	lämpötila ulkona
3	battery power	1296	2065	2108	1931	kW	
4	battery state of charge	527	2083	2098	1929	%	
5	conditional power moving	1326	2063	2099	1932	kW	loggaa vain liikkeessä
6	conditional power stopped	1330	2075	2092	1924	kW	loggaa vain paikallaan
7	current gear	476	2072	2096	1935		1, 0 tai -1 riippuen kulkusuunnasta
8	distance	489	2082	2103	1927	km	matkamittarin lukema
9	door status	508	2069	2089	1922		0 = vähintään yksi ovi auki, 1 = viimeinen ovi sulkeutumassa, 2 = ovet kiin
10	energy consumed	528	2078	2107	1920	kWh	lukema nollautuu kun auto sammutetaan
11	Latitude	375	2080	2102	1925		
12	Longitude	376	2074	2105	1917		
13	parking brake status	535	2068	2101	1918		1 = jarru päällä, 0 = jarru pois päältä
14	passengers	526	2077	2106	1930		ei toimi, arvona vakio 250
15	service brake air pressure 1	521	2073	2104	1933	kPa	
16	service brake air pressure 2	522	2081	2088	1936	kPa	
17	speedTCO1	1034	2064	2090	1919	km/h	
18	Uptime	410	2079	2095	1923	h	WRM laitteen uptime
19	vehicle motion	1324	2071	2097	1926		1 = auto liikkeessä, 0 = auto paikallaan
20							

Figure 12. *Codes of e-buses and variables in provided BACPAC file*

3.2 Managing the data via Microsoft SQL

To open the table with the data in SSMS tool, inner Microsoft SQL language is used. It should be mentioned in the code which parameter is needed to be shown. Figure 13 demonstrates the code used to see the collected variables from the table named dbo.energy_hourly.

SQLQuery1.sql - M...ART\marsmart (59))*

```sql
/****** Скрипт для команды SelectTopNRows из среды SSMS  ******/
SELECT [pvm]
      ,[klo]
      ,[busId]
      ,[nodeId]
      ,[Summa]
  FROM [eBus].[dbo].[energy_hourly]
```

Figure 13. *SQL Query for proceeding the table with collected data of energy use per hour for 4 e-buses*

All the requested variables are shown after command "SELECT". Among those are dates, hour of the day, bus ID, node ID (showing the ID used for the data related to energy consumption), sum of the variable per hour. The name of the table is given as a reference for the place where the data should be taken from.

The query gave the table with all the rows of related information. Figure 14 shows the requested parameters and their appearance in the SSMS tool. The table consists of 7204 rows which means, that for all 4 electric buses energy consumed during operation was collected for 7204 hours.

Результаты | Сообщения

	pvm	klo	busId	nodeId	Summa
7189	2017-10-18	09.00	256	528	1.200000
7190	2017-10-08	17.00	256	528	21.200000
7191	2017-10-24	07.00	256	528	9.900000
7192	2017-10-24	12.00	256	528	20.600000
7193	2017-10-17	14.00	256	528	10.100000
7194	2017-09-27	12.00	256	528	3.800000
7195	2017-10-09	16.00	256	528	21.900000
7196	2017-10-26	15.00	256	528	13.300000
7197	2017-10-07	18.00	256	528	11.300000
7198	2017-10-19	07.00	256	528	11.000000
7199	2017-10-30	11.00	256	528	20.400000
7200	2017-09-26	07.00	256	528	2.400000
7201	2017-10-26	17.00	256	528	39.300000
7202	2017-10-28	17.00	256	528	16.100000
7203	2017-10-09	13.00	256	528	22.000000
7204	2017-10-24	22.00	256	528	20.200000

Запрос успешно выполнен.

Figure 14. *Result in the table from proceeding the SQL query for hourly energy consumption from 4 e-buses*

To separate all the 4 buses in the data command "WHERE" is used. Bus ID's are given in the table on Figure 13. Thus, Figure 15 illustrates the result of requesting the information about the hourly energy consumption of the bus with the ID 256.

Результаты | Сообщения

	pvm	klo	busId	nodeId	Summa
2555	2017-10-18	09.00	256	528	1.200000
2556	2017-10-08	17.00	256	528	21.200000
2557	2017-10-24	07.00	256	528	9.900000
2558	2017-10-24	12.00	256	528	20.600000
2559	2017-10-17	14.00	256	528	10.100000
2560	2017-09-27	12.00	256	528	3.800000
2561	2017-10-09	16.00	256	528	21.900000
2562	2017-10-26	15.00	256	528	13.300000
2563	2017-10-07	18.00	256	528	11.300000
2564	2017-10-19	07.00	256	528	11.000000
2565	2017-10-30	11.00	256	528	20.400000
2566	2017-09-26	07.00	256	528	2.400000
2567	2017-10-26	17.00	256	528	39.300000
2568	2017-10-28	17.00	256	528	16.100000
2569	2017-10-09	13.00	256	528	22.000000
2570	2017-10-24	22.00	256	528	20.200000

Запрос успешно выполнен.

Figure 15. *Result in the table from proceeding the SQL query for hourly energy consumption from the bus with ID 256*

Thus, for the bus with ID 256 the number of hours collected for the energy consumption is 2570 h. For the buses with ID’s 1855, 1884 and 1911 the numbers of hours are 1573 h, 1699 h and 1362 h, respectively.

For the further analysis of the data, additional commands used in SQL queries are “AVG’ and “SUM”. “AVG” calculates the average number among all the numbers in the requested column. “SUM” calculates the sum of all the numbers in the specified column.

4. THE ENERGY CONSUMPTION OF EBUSES

Traditional diesel buses in cities are a clear target for a change to battery electric buses because of the low-range distances within bus routes and availability for a complete planning those routes. Researches and development of technologies for electric buses also lower the difference in payback time between diesel buses and eBuses. Thus, the next steps can be taken towards the analysis and improvement of performance of electric buses in the cities.

One of the main interests in such analyses of the performance of electric buses is the energy consumption. There are many factors affecting the energy consumption. There are also several ways of analyzing such factors.

4.1 The influence of different factors on energy consumption of eBuses

Large amount of studies of energy consumption in eBuses directed towards increasing the driving range of the bus and, in the same time, decreasing the capacity and cost of the battery inside the bus. However, bringing together all the pieces affecting the energy consumption of eBuses on the road plays significant role in analysis done in this work.

Imagining the same route for one electric bus in different driving conditions can help better with understanding this concept. Collected real-time data from for electric buses within one year presented in this work provides a chance to see, that even though all the buses are the same and the route is also the same all the time, the energy consumption of e-buses differentiates from hour to hour, day to day, month to month. Previous studies in this field show, that the actual performance of e-bus battery is not the same which is caused by different environmental conditions.

The first factor affecting the energy consumption is the weather. It can be the temperature in which electric bus operates. The outside temperature changes the battery behavior if it is not within the recommended for this battery limits. For example, cold batteries hold a charge worse and the charging of the battery itself behaves not in its normal way because of stronger resistance.

Warmer or colder environmental temperature affects not only the battery itself, but also brings a discomfort for passengers which leads to the usage of additional heating or cooling inside the bus. Such circumstances also lead to disturbing the standard performance condition of the battery in electric bus.

Another influential factor for the battery performance is the type of the road an electric bus is driven on. Roads can also be affected by the weather which may require an additional energy from the battery to make the bus overcome those conditions such as, for instance, fresh snow on the road. Moreover, roads can be unexpectedly damaged or brought into reinforcement condition which is also differentiates the energy consumption. The type of the road with ups and downs is another example for this situation, however that moment is static, thus considered in collected data.

Finally, the energy consumption of the battery electric bus can be simply affected due to different driving methods. One driver may push the gas pedal harder than another one or turn the wheel in the place on the road where the other driver would just drive straight.

All the conditions stated above are being currently studied. Those can be better understood from researches of the real-time data taken from the electric buses together with analyzing those.

4.2 The influence of the accuracy of energy consumption on calculations of other aspects of proper eBuses operation

The accuracy of collected data of energy consumption of eBuses has an effect on many different aspects of future development and economy when changing diesel buses to eBuses. Generally said, it helps to get more precise results in reality. If the collected data is more accurate and is properly analyzed, then eBuses infrastructure with the same reliability might have less costs.

The part necessary for eBuses operation, that can be significantly affected by the energy consumption accuracy is the location of charging infrastructure. If batteries, route and eBuses remain the same with different accuracy of the energy consumption, the amount of necessary charging points, for example, on the bus stops may become less or more frequent for eBuses implemented in the future. The beneficial amount of charging stops requires its placement where they will be most used, and the investment justified. Thus, planning on the location of charging infrastructure requires high accuracy to be the most beneficial and the more precise information on the energy consumption of eBuses is necessary.

Mostly the bus stops selected for charging infrastructure are located in the inner-city [20]. The location of each charging station requires the information about the charging level of eBus battery at the beginning of the route, distance traveled with eBus, the energy consumed and maximum battery capacity [20].

The accuracy of energy consumption data also provides all the calculations, related to cash flows or life cycle costs, eBuses' battery use and even route planning, with closer to reality image. Thus, the future development in terms of better data collection will bring a significant value.

4.3 Energy consumption of Tampere e-buses

First, it must be mentioned, that the provided real-time data collected from e-buses is not consistent. It means, that the data was not collected for every single day from the starting operation point of e-buses. Moreover, all eBuses were not on the road every single day.

4.3.1 Energy consumption per hour

The data consists of 7204 hours of collected energy consumption in total. Moreover, all the consumed energy of each bus was summarized from every 5 seconds data to every operating hour.

The first calculations are done for the bus with ID 256. The starting date for collecting the energy consumption data from the bus was 26 September 2017. Thus, taking into consideration only autumn time, dates in the program code are from 1 September 2017 till 1 December 2017. It appears, that the bus was in operation for 397 hours during this period of time. Figure 16 demonstrates the code written for calculating the average amount of energy consumed per hour during autumn and the energy consumed in kWh/h.

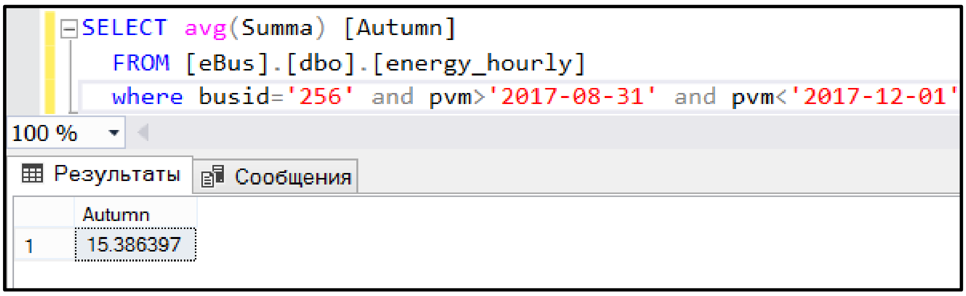


Figure 16. *Average amount of consumed energy per hour of the bus 256 during autumn 2017*

Thus, the average amount of the hourly energy consumed for the first bus with ID 256 is approximately 15.39 kWh/h. In the same manner the average amounts of hourly energy consumption of that bus during different seasons are calculated.

During the wintertime from 2017-11-30 to 2018-03-01, the bus with ID 256 has the average energy consumption around 16.52 kWh/h. The number of hours used for calculations is 670 which is almost twice higher compare to autumn case. However, that change with the number of rows used adds only a bit of accuracy to defined average energy consumption value, but the value in general does not have too much difference.

During the springtime from 2018-02-28 to 2018-06-01, the electric bus 256 average energy consumption was approximately 15.34 kWh/h. The number of hours used for calculations is 565. Defined average energy consumption value already shows, that during the wintertime the energy consumption was higher (for approximately 1.2 kWh/h) compare to month with more warm weather. Figure 17 shows the average maximum and minimum temperatures for each season from 2017-08-31 to 2018-09-01. [23]

	Avg Maximum Temperature, degC	Avg Minimum Temperature, degC
Autumn (2017-08-31 - 2017-12-01)	8,13	4,51
Winter (2017-11-30 - 2018-03-01)	-1,9	-6
Spring (2018-02-28 - 2018-06-01)	9,87	0,13
Summer (2018-05-31 - 2018-09-01)	22,8	14,6

Figure 17. *Average maximum and minimum temperatures for each season from 2017-08-31 to 2018-09-01*

The summertime from 2018-05-31 to 2018-09-01 demonstrated even lower average amount of energy consumed which is 14.34 kWh/h. The electric bus with ID 256 was in operation only for 366 hours during that period. Thus, it is easy to see the tendency of decreasing the average energy consumption per hour from colder to warmer times of the year. It results in approximately 1 kWh/h difference between adjacent seasons. Figure 18 shows all the results with the code used to define average energy consumption values for all four seasons.

```
SELECT avg(Summa) [Autumn]
  FROM [eBus].[dbo].[energy_hourly]
  where busid='256' and pvm>'2017-08-31' and pvm<'2017-12-01'
SELECT avg(Summa) [Winter]
  FROM [eBus].[dbo].[energy_hourly]
  where busid='256' and pvm>'2017-11-30' and pvm<'2018-03-01'
SELECT avg(Summa) [Spring]
  FROM [eBus].[dbo].[energy_hourly]
  where busid='256' and pvm>'2018-02-28' and pvm<'2018-06-01'
SELECT avg(Summa) [Summer]
  FROM [eBus].[dbo].[energy_hourly]
  where busid='256' and pvm>'2018-05-31' and pvm<'2018-09-01'
```

	Autumn
1	15.386397

	Winter
1	16.520895

	Spring
1	15.336991

	Summer
1	14.340710

Figure 18. *Code used to define the average energy consumption values on the left and all the results from it on the right*

Then, the other three buses hourly energy consumptions are calculated by the same way. The results from all four buses are provided in the Table 1.

Table 1. Average energy consumption for all 4 Tampere electric buses during different seasons of the year

	Bus 1 (ID 256)		Bus 2 (ID 1855)		Bus 3 (ID 1884)		Bus 4 (ID 1911)	
	Amount of hours on the road, h	Average energy consumed per hour, kWh/h	Amount of hours on the road, h	Average energy consumed per hour, kWh/h	Amount of hours on the road, h	Average energy consumed per hour, kWh/h	Amount of hours on the road, h	Average energy consumed per hour, kWh/h
Autumn	572 (2018)	14.62 (2018)	904	15.02	834	14.4	843	14.88
Winter	670	16.52	The data was not collected					
Spring	565	15.34						
Summer	366	14.34	669	15.89	865	15.51	519	15.72

The operation of buses with ID's 1855, 1884 and 1911 started in the beginning of summer 2018. Thus, the data for two seasons (i.e. winter and spring) was not collected at the moment of analyzing the data for the current thesis work.

The fluctuations among the values for different buses during the same season might relate to the driving differences. For instance, during the same road different traffic situations might appear. Thus, constant changing the driving condition forces the battery to give more or less energy which results in different average values shown in the Table 1.

Figure 19 helps to visualise the difference in average energy consumption per hour of four eBuses during different seasons. From the diagram it is easy to see, that among all the seasons the energy consumption variates within the same limit 14 kWh/h – 16 kWh/h.

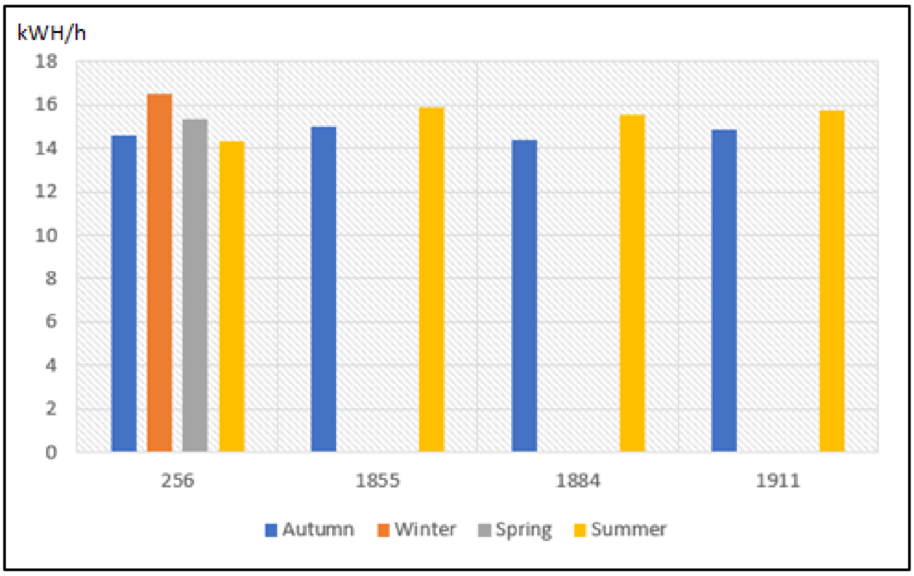


Figure 19. *Diagram of energy consumption per hour for four eBuses during different seasons of the same year*

As it was stated in the chapter 4.2, the cold outside temperature makes electric bus battery to have a slightly worse performance. From the Table 1, the difference between average energy consumed between conditions when the bus is operated in the cold weather and the warm weather is quite noticable. The fluctuation between values is approximately 1-2 kWh/h. It happens, because during the winter time the battery of electric vehicle works not in its natural condition. First, the reason to that is the coldness itself. Secondly, the operation of the bus requires to turn on the heating system for the people inside the bus to feel more comfortable during the cold days.

Moreover, another moment affecting the hourly average energy consumption might be the road on which e-buses are operated. During the winter time it is covered with snow and ice which makes a vehicle to use more energy to start it from the ground.

4.3.2 Energy consumption per day

For the calculation of average energy consumption per day for electric buses, the days when each e-bus operates full hours in different months were considered. However, it is difficult to compare the energy consumption of electric buses per day, because generally the daily consumption of energy is highly depended on each bus driver driving routine, the working schedule of the bus and the distance travelled by bus at that day.

Most commonly, every bus was operating 16 hours for a full working a day. However, some days buses were operating only for 2-3 hours which certainly brings less energy consumed by e-buses per day. Figure 20 demonstrates the full operating day of the bus with ID 256 and energy consumed every hour.

```
SELECT TOP (1000) [pvm]
      ,[klo]
      ,[busId]
      ,[nodeId]
      ,[Summa]
  FROM [eBus].[dbo].[energy_hourly]
  WHERE busId='256' AND pvm LIKE '2018-10-02'
  ORDER BY klo


  SELECT SUM (Summa) [Total Energy Consumed]
  FROM [eBus].[dbo].[energy_hourly]
  WHERE busId='256' AND pvm LIKE '2018-10-02'
```

	pvm	klo	busId	nodeId	Summa
1	2018-10-02	07.00	256	528	19.400000
2	2018-10-02	08.00	256	528	12.900000
3	2018-10-02	09.00	256	528	12.600000
4	2018-10-02	11.00	256	528	25.600000
5	2018-10-02	12.00	256	528	12.800000
6	2018-10-02	13.00	256	528	12.800000
7	2018-10-02	14.00	256	528	12.100000
8	2018-10-02	15.00	256	528	12.100000
9	2018-10-02	16.00	256	528	12.300000
10	2018-10-02	17.00	256	528	14.400000
11	2018-10-02	18.00	256	528	12.700000
12	2018-10-02	20.00	256	528	23.200000
13	2018-10-02	22.00	256	528	24.200000

	Total Energy Consumed
1	207.100000

Figure 20. *Full operating day for a bus 256 with total energy consumed during that day*

Thus, the electric bus with ID 256 consumed 207.1 kWh during the full operating day in Autumn 2018. The working day started at 7 am and continued till 22 pm which is regular bus working schedule in Tampere, Finland.

As it is possible to see from the example above, the energy consumptions per hour are different from each other. For instance, at hour 13:00 electric bus consumed 12.8 kWh, but during the next hour at 14:00 it consumed less – 12.1 kWh. This could be the result of traveling different distances hourly, driving speeds, stops which affect that value. Table 2 illustrates the distances bus 256 travelled during the same hours taken from the provided data (it has more rows because in this table no hours were skipped while collecting the data about the distances).

Table 2. *Distances travelled every hour for a bus 256 during 02 October 2018*

	BusId	Day	Time	Distance, km
1	256	02 October 2018	6:00	13.1
2			7:00	10.44
3			8:00	10.9
4			9:00	10.88
5			10:00	10.84
6			11:00	11.07
7			12:00	10.6
8			13:00	10.23
9			14:00	11.87
10			15:00	10.86
11			16:00	9.79
12			17:00	11.92
13			18:00	10.76
14			19:00	11.55
15			20:00	10.83
16			21:00	16.87
17			22:00	1.47

After comparison of Table 2 and Table 3, it is possible to see how the distances travelled by the same bus vary, even though it was driven on the exact same route. However, the same comparison may bring to notice that the correlation between distance and the energy consumed is not showing what expected. For example, the energy consumed during hour 14:00 is exactly the same as during the hour 15:00, but the difference between distances during those hours is 1 km. This might be the result from various traffic occurrences such as traffic jams, longer time while waiting on passengers on the bus stops or even different speed of that bus which results in lower hourly traveled distance. Moreover, this can be the result from different waiting times in the end stop for different buses which leads to different driving times during the day. For instance, one bus may arrive to the end stop at 13:59, and another at 14:01 which results in difference in distance data collection.

The calculation of the daily energy consumed for electric bus with ID 256 during few days was also made. Table 3 shows the total daily energy consumption of the e-bus 256 and the total distance travelled during the same days. Thus, during some days the total energy consumed during those days can fluctuate from the total distance traveled by the electric bus dependently on traffic routines or bus driver driving behavior.

Table 3. *The total daily energy consumption of the e-bus 256 and the total distance travelled during the same days*

	BusId	**Day**	**Energy consumed, kWh**	**Distance traveled, km**
1	256	01 August 2018	0.7	0.16
2		13 August 2018	109.4	107.06
3		14 August 2018	197.3	192.44
4		15 August 2018	222.7	198.83
5		16 August 2018	113.1	106.65
6		17 August 2018	233.2	187.01
7		18 August 2018	200.2	183.77
9		20 August 2018	78.7	41.26

4.3.3 Energy consumption per month

Another interesting point from analyzing the data of Tampere electric buses is the average monthly energy consumption during different year seasons. For the analysis in this chapter, sums of energy consumed during different months for each bus were calculated first. Again, buses with ID's 1855, 1884 and 1911 were not set to collect the data during the winter and spring times on the moment of writing this work. Thus, for those three buses, only average monthly energy consumption during summer and autumn were calculated.

It has to be considered for the analysis, that all the busses have different operating schedules even if they are operating in the same days. For example, one eBus can be driven on one route twice a day and another eBus can be on the same route four times the same day. Thus, the travelled distances and hours operated might differ significantly. However, either way every bus average monthly energy consumption can be considered as the reference point for the future assumptions and calculations. As an example, Table 4 demonstrates the result from calculation of monthly energy consumptions of all buses during each month in autumn 2018.

Table 4. *Sums of the energy consumed by each of four electric buses for each month during autumn period*

	Energy consumed (BusId 256), kWh	Energy consumed (BusId 1855), kWh	Energy consumed (BusId 1884), kWh	Energy consumed (BusId 1911), kWh
September	3938.8	5907.6	4653.8	5730.7
October	4422.4	4587	5016.1	4904.6
November	4044.9	3083	2335.9	1904

From the example above, it could be mentioned, that all the calculations were made for the same year and the same months when e-buses were operating. However, the difference in total energy consumed per month is crucial for each bus. It variates from approximately 200 kWh to 2000 kWh. Nevertheless, such big difference is dependent mostly on each bus working schedule. Further, during the next months buses were set in the schedule in a way, that the less working buses in previous months are working more and the other way around. Thus, the total energy consumption among all the e-buses during few months fluctuates less.

Table 5 illustrates the total energy consumed by each bus during every season in 2018. The variation among all the energy consumptions during the same seasons is less than when it is compared in monthly energy consumptions. Now it variates from about 100 kWh to 3000 kWh.

Table 5. *The total energy consumed by each of four Tampere e-buses during different seasons in 2018*

	Total energy consumed per season, kWh			
	Bus 256	**Bus 1855**	**Bus 1884**	**Bus 1911**
Autumn	12406.1	13577.6	12005.8	12539.3
Winter	11070	The data was not collected		
Spring	8665.41			
Summer	5248.68	10629.51	13410.81	8159.91

Thus, the average monthly energy consumption can be considered closer to the real numbers when calculated for few months. According to that, the next calculations were made as an average energy consumption of each electric bus per month during the operated seasons. Table 3 illustrates the result of that calculation where average monthly numbers are shown separately for each season.

Table 6. *Average monthly numbers of the energy consumption for different seasons and different electric buses*

	The average energy consumption per month, kWh			
	Bus 256	**Bus 1855**	**Bus 1884**	**Bus 1911**
Autumn	4135.37	4525.87	4001.93	4179.77
Winter	3689.67	The data was not collected		
Spring	2888.47			
Summer	1749.56	3543.17	4470.27	2719.97

From the provided Table 6, it could be seen, that the difference in average monthly energy consumption for all the electric buses fluctuates quite high. One of the most probable explanations to that is working schedule. From the numbers for bus 256 the average energy consumption per month decreases from the autumn season to the summer season.

The reason to that change might be that the operating hours and holidays differ during each season. However, after comparison the average monthly energy consumption of the bus 256 to the other three buses, most likely the schedule from that bus was set in a way, that during the summer it was operated less often than buses 1855, 1884 and 1911 during the summer 2018.

The visual representation of average energy consumption each month for 4 eBuses is demonstrated in Figure 21. The difference between monthly energy consumption in this case is quite noticeable. The bar for the eBus 1884 summertime energy consumption is higher than during autumn time which is completely opposite compare to other 3 buses.

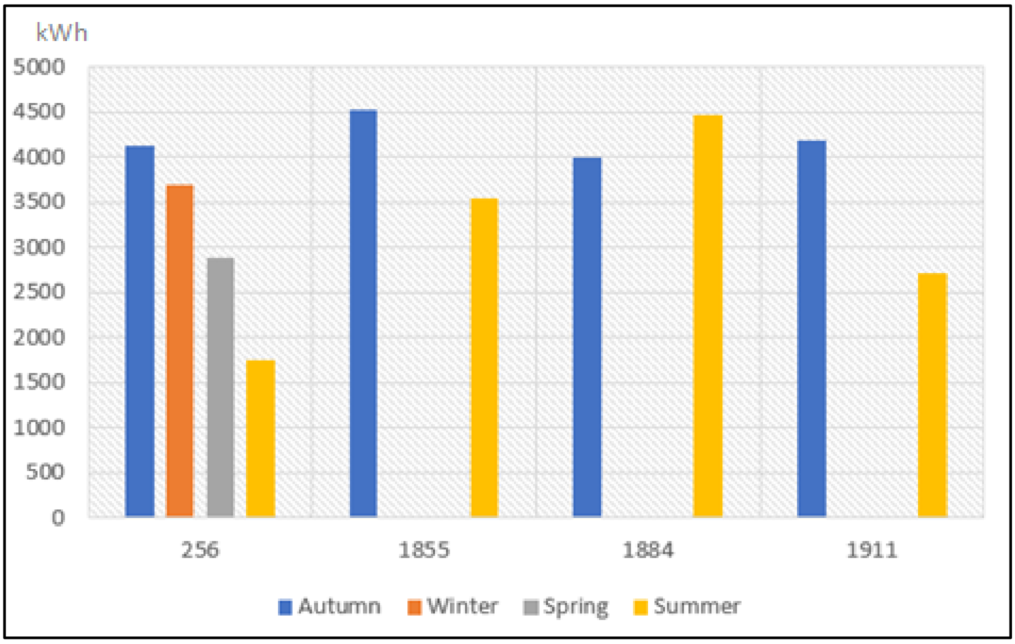


Figure 21. *Average monthly energy consumption for four eBuses during different seasons*

If Figure 21 is compared to Figure 19, the pattern of average energy consumptions in both cases is not equal, even though it logically should be. For example, in Figure 19 it was obvious, that during winter and spring average hourly energy consumption was higher than in Figure 21 with average monthly energy consumption for the same four eBuses. Moreover, the variations among bars of the same season in those two diagrams is significantly high. For instance, in Figure 19 bars in summertime for different buses is almost the same to each other which is completely opposite to the same bars from Figure

21 where difference is quite noticeable. The reason to that is most likely different monthly schedules for all four eBuses, but more or like average season schedule is similar for the same eBuses.

It could be said, that the biggest reason to both differences is different times spent on the route for each eBus. EBuses consume almost the same amount of energy per hour, but the variations in driving schedules cannot put average monthly consumption to the same way of comparison. For example, according to Figure 21, one may say, that eBus 256 was operating way less hours during summertime compare to eBus 1884 during the same season.

Another reason which has slightly less valuable impact on fluctuations among average energy consumptions calculated for different periods of time is the driving behavior. However, the affect from this reason would not be as significant as from the first one, because all four eBuses still operate on the same route.

4.3.4 Energy consumption per kilometer

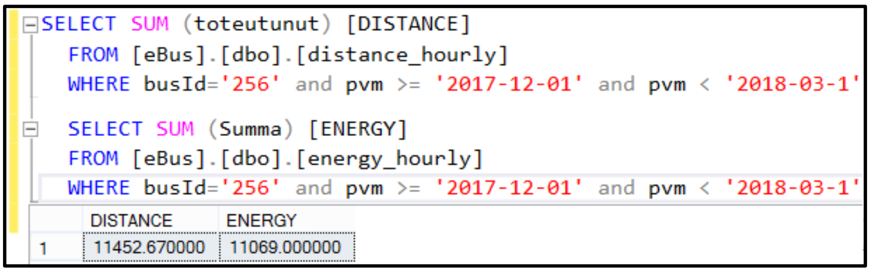
The next chapter will be about the analysis of energy consumption per kilometer of all four Tampere electric buses. The point of such analysis is to separate all the factors such as e-bus operating schedule, different distances traveled and minimize the effect of driver driving behavior on the comparison of energy consumption during different weather condition where electric buses were operated.

The calculation was made in the form where the sum of all the distance traveled by each bus per season was divided by the total energy consumed during the same season and the same bus. Figures 22-2 demonstrate queries for calculations of sums for every season for the bus with ID 256. Sums of energy consumed per hour, and distance traveled per hour are calculated first for different seasons of the year, then the average energy consumed per kilometer is found by dividing energy sum to distance sum.

```
SELECT SUM (toteutunut) [DISTANCE]
  FROM [eBus].[dbo].[distance_hourly]
  WHERE busId='256' and pvm >= '2018-09-01' and pvm < '2018-12-1'
  SELECT SUM (Summa) [ENERGY]
  FROM [eBus].[dbo].[energy_hourly]
  WHERE busId='256' and pvm >= '2018-09-01' and pvm < '2018-12-1'
```

	DISTANCE	ENERGY
1	7897.750000	8361.200000

Figure 22. *Query in SSMS and results of its application for bus 256 (Autumn time)*

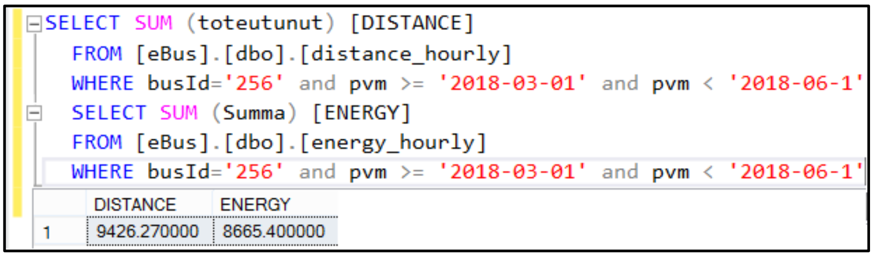


```
SELECT SUM (toteutunut) [DISTANCE]
  FROM [eBus].[dbo].[distance_hourly]
  WHERE busId='256' and pvm >= '2017-12-01' and pvm < '2018-03-1'

  SELECT SUM (Summa) [ENERGY]
  FROM [eBus].[dbo].[energy_hourly]
  WHERE busId='256' and pvm >= '2017-12-01' and pvm < '2018-03-1'
```

	DISTANCE	ENERGY
1	11452.670000	11069.000000

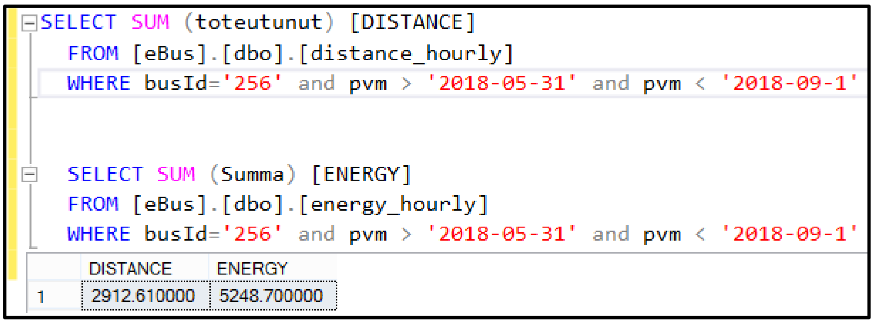
Figure 23. *Query in SSMS and results of its application for bus 256 (Winter-time)*



```
SELECT SUM (toteutunut) [DISTANCE]
  FROM [eBus].[dbo].[distance_hourly]
  WHERE busId='256' and pvm >= '2018-03-01' and pvm < '2018-06-1'
  SELECT SUM (Summa) [ENERGY]
  FROM [eBus].[dbo].[energy_hourly]
  WHERE busId='256' and pvm >= '2018-03-01' and pvm < '2018-06-1'
```

	DISTANCE	ENERGY
1	9426.270000	8665.400000

Figure 24. *Query in SSMS and results of its application for bus 256 (Spring-time)*



```
SELECT SUM (toteutunut) [DISTANCE]
  FROM [eBus].[dbo].[distance_hourly]
  WHERE busId='256' and pvm > '2018-05-31' and pvm < '2018-09-1'


  SELECT SUM (Summa) [ENERGY]
  FROM [eBus].[dbo].[energy_hourly]
  WHERE busId='256' and pvm > '2018-05-31' and pvm < '2018-09-1'
```

	DISTANCE	ENERGY
1	2912.610000	5248.700000

Figure 25. *Query in SSMS and results of its application for bus 256 (Summer-time)*

Table 7 presents all the results from that calculation. Thus, it appears, that the energy consumption of all the buses variates from around 1 kWh/km to 1.8 kWh/km during different seasons.

Table 7. *Average energy consumption per kilometer for all four electric buses during different seasons of the year*

	Energy consumed per kilometer, kWh/km			
	Bus 256	**Bus 1855**	**Bus 1884**	**Bus 1911**
Autumn	1.06	1.09	1.15	1.12
Winter	0.97	The data was not collected		
Spring	1.09			
Summer	1.8	1,44	1.23	1.7

The difference in energy consumption between cold months and warm months it noticable. It fluctuates from approximately 0.2 kWh to 0.8 kWh. All the calculations were made assuming that the whole data was taken and collected correctly and recorded distances were true for recorded energy consumption.

Energy consumed by eBus during winter is noticably lower than energy consumed per kilometer during summertime. The reason to that most likely is intensively working cooling system during the operation time of eBuses.

Provided data also shows, that the worst hours in terms of energy consumption appeared to be 8-9:00 and 12-13:00 pm with consumption around 40-50 kWh. Most likely, those hours are the most active in terms of eBuses operation during days.

From the visual representation of average energy consumption per km for every eBus in Figure 26, bars for the values calculated for summertime stand out significantly from other seasons. This signifies that the operating condition for Tampere eBuses is completely different for summer season. It might be due to the usage of condition systems, more people traveling by public transport, frequent door opening during warm period and different speed/acceleration levels of eBuses when they are driven. However, the reason to such weighty difference is most likely because of inaccurate data collection.

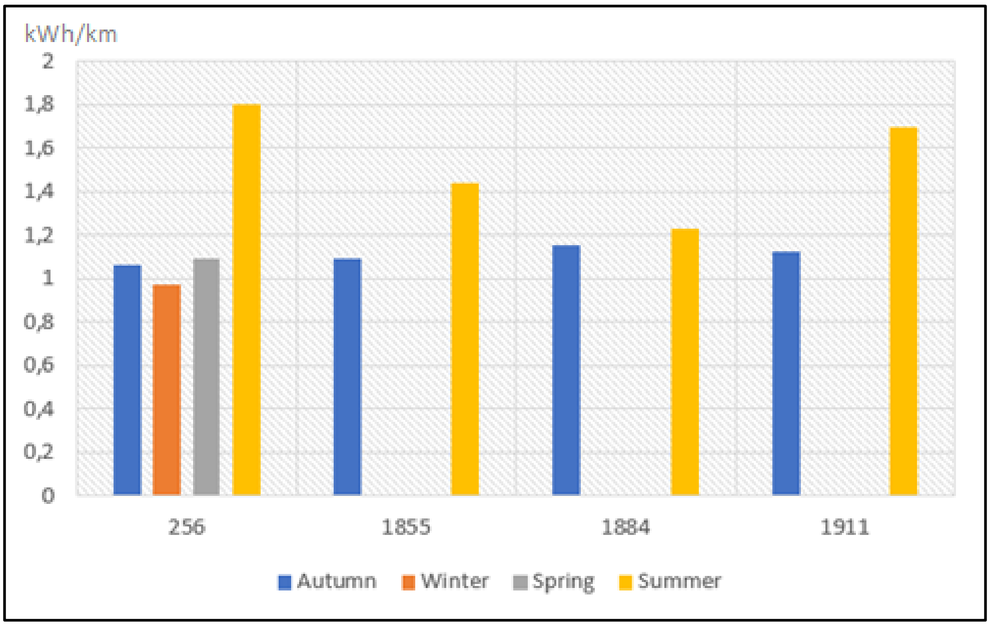


Figure 26. *Diagram of average energy consumption per km for four different eBuses during different seasons*

According to [21], the total weight of the bus including the amount of passengers is strictly correlated with the propulsion energy consumption. With the differense in approximately 55 people, the energy consumption of eBus can change up to 0.25 kWh/km, according to Espoo case in [21], which seems to be one of the possiblities noticed among the results stated in Table 4. This could also be a reason why the energy consumption of eBus 256 during the winter time appeared to be lower than during the other months. Finland has quite short sunny time during winter and the temperature outside can reach -30 0C, that is why more people prefer staying inside their houses which leads to less amount of people using the public transportation. In this case, the weight of eBuses could be lower during winter which leads to lower propulsion energy consumption.

Together with the statement above, [21] gives and idea, that door opening has also small effect on energy consumption of eBuses. If every time 3 doors are opened and closed, about 0.001 kWh of energy is used from the bus battery. However, during winter time due to cold outside temperature, bus drivers tend to open all doors as little times as possible which is opposite to summer time. That happens, because during cold winter time it is more comfortable for passengers and drivers themselfes to stay inside the bus with warmer temperature, and if the doors are open more often, then the temperature inside significantly decreases which is, again, the opposite to summer time.

4.4 Conclusion on collected data and results from calculations of energy consumption for different periods of time

From all the collected data and calculations, it is obvious, that the most important moment for such research is the accurate data. That will give more precise results.

In terms of analysis of large time periods of energy consumption, it could be said, that to compare eBuses among each other the operation schedules play significant role. Every eBus travels different distances every day, week, month or season. Thus, the best option to compare the same eBuses and their operating characteristics (this work specifically concentrates on energy consumption) is for shorter periods of time or accordingly to the same travelled distances.

When calculations for each eBus energy consumption is made for the same travelled distance, the results give better picture on different aspects for comparison. In that case, monthly or seasonable schedules play smaller roles. However, the driving routine, each eBus characteristics and time of the year play much bigger role in that situation.

5. IMPLEMENTATION OF CALCULATIONS TO PREVOUSLY STUDIED FEASIBILITY OF EBUSES IN PUBLIC TRANSPORTATION

The analysed data can be the basis for comparison of previous theoretical researches of feasibility of eBuses in public transportation with approximate real collected and proceeded data in previous chapters of this work. The results of the energy consumption calculated in this work is not 100% exact, because of the way that data was collected. For instance, some dates were skipped, some eBuses were not operating during certain days which means that the data collection was not absolutely consistent. However, the received database is still closer to reality than any theoretical assumptions. Thus, this chapter will examine the previous studies on feasibility of eBuses in public transport which then will be reviewed from the comparison to real data point of view.

5.1 Introduction to previows studies of the economic feasibility of eBuses in a mid-sized city [21]

Replacing one of the public transportation units such as diesel buses to eBuses requires certain changes in infrastructure. The changes require building charging stations, strengthening the electric grid, even altering the operating schedule, etc. However, economic point of view on comparing eBuses to diesel buses includes the cost of every part of the complete interchangeable functionality of both types of buses.

In [21] all the prices were taken related to Finland, and the data provided for this work is also taken from Tampere which is city in Finland. Thus, with this match it will be more probable to get the better understanding of the situation after comparison the results of energy consumption of eBuses calculated in this work to assumed energy consumption in [21].

To compare the complete estimated cash flow of four diesel buses to four eBuses certain parameters were taken. Among those are fuel/energy cost, fuel/energy consumption, the maintenance cost, battery cost, prices of buses, prices of charging stations etc. The cash flow analysis of the costs was implied for the end stop charged LTO bus line in Table 8 and for diesel bus line in Table 9 with the discount rate of 3 %. In Table 9 NPV is shown for years 2015-2026. First year costs include the investment costs of buses and the charging infrastructure costs for eBuses. Then, the maintenance and fuel or energy costs take place every day. The LTO bus battery change takes place after 6.5 years. [21]

Table 8. *Cash flow for 4 eBuses with 42 kWh LTO batteries from 2015 till 2026 (numbers in 1000 €) [21]*

Year	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026
Buses	1629	91	91	91	91	91	309	91	91	91	91	91
Infra	224	4	4	4	4	4	4	4	4	4	4	4
NPV												2911

Table 9. *Cash flow for 4 diesel buses from 2015 till 2027 (numbers in 1000 €) [21]*

Year	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026
Buses	1204	204	204	204	204	204	204	204	204	204	204	204
NPV												3095

From the tables it is clear, that in 12-year period eBuses with 42 kWh LTO batteries will start to save more money compare to diesel buses. All the years till 2026 were assumed to have the same prices. However, all the roughly estimated prices should be checked from the manufacturer and will probably be slightly different with time.

After 12 years Net Present Value for eBuses with 42 kWh LTO batteries is lower than for diesel buses up to 184 000 €. The visual representation for both cash flows (costs) without implementation of the results from energy consumption calculations in this work are demonstrated in Figure 27.

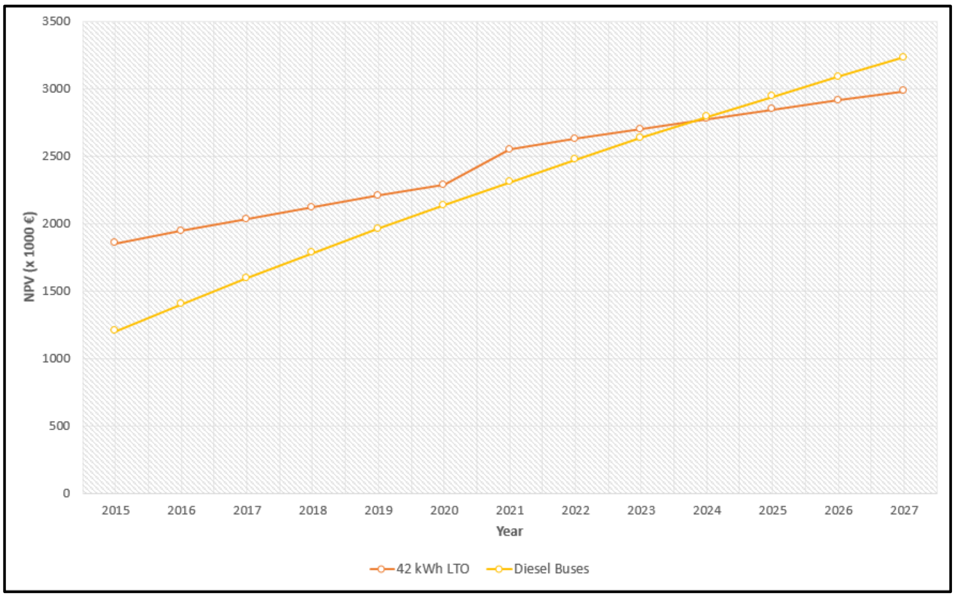


Figure 27. *Cash flows diagram for both cases without the changes in energy consumption accuracy taken from this work results*

The fact that batteries for eBuses as well as other parts necessary for its operation become cheaper with time, gives an idea, that calculated NPV for eBuses in tables above can be even lower in the future.

The discussion of changing prices in the industry for eBuses, its part and details, charging infrastructure are neglected in this work. However, with the data results calculated in Chapter 4.2 (especially in 4.2.4) could be used to have a rough analysis of [21] and be compared to estimated energy consumption in [21] to see the correctness of theoretical estimations and to see the results closer to reality.

5.2 Implementation and analysis of calculated energy consumption per km results to estimated results in previous researches of economic feasibility of eBuses

This chapter concentrates on estimated analysis and comparison of calculated energy consumption results to estimated results in [21] to calculated further average energy consumptions for four eBuses from Tampere case. That will give an overview on how close the calculated results for lifetime costs (Tables 8 and 9) to the real-life example. It will also show how much the theoretical calculations will differ after implementation of actual eBuses operation data.

For the comparison, all the values used in [21] except energy consumption are assumed to be the same. Moreover, the annual average energy consumptions per kilometer for all four Tampere eBuses are presented in Table 11.

Table 10. *Average energy consumption per kilometer for all four Tampere eBuses during the complete year*

	Energy consumed per kilometer, kWh/km			
	Bus 256	**Bus 1855**	**Bus 1884**	**Bus 1911**
Year 2017-2018	1.228	1.267	1.194	1.4

The batteries used in Tampere eBuses are equipped with High Power batteries of 75 kWh [24]. The difference in energy consumption between eBuses with such types of batteries is not as significant as the difference between theoretical values and values from real-time performances. Such difference between 42 kWh and 75 kWh batteries power would result in a small size and weight difference between buses which does not affect the energy consumption significantly. Therefore, the difference between buses with different battery types was not taken into account and calculated values in this work were used as the alternative for values in [21].

Thus, Table 10 demonstrates, that each of four Tampere buses consume more energy than it was assumed in [21]. The difference variates from 0.194 kWh/km to 0.4 kWh/km for eBuses with 42 kWh LTO batteries which is quite significant (assumed energy consumption for eBuses with those batteries in [21] was 1 kWh/km).

If all of four Tampere buses would travel the exact same distances as it was assumed in [21], then it would be 70 000 km per bus in a year. In real-case Tampere eBus traveled approximately 30 000 km per year. However, for better comparison it is considered as it was in [21]. Discount rate will be taken the same (3 %). Moreover, to concentrate only on difference in cash flows for energy consumption, this work assumes the exact same price for electricity in Finland which was considered 0.079 €/kWh without VAT and with a distribution network grid fee. As a result, the additional costs (appear to be higher) for energy consumption of eBuses with different batteries for years 2015 – 2026 are added to Table 11 and presents it accordingly to possible difference between actual and theoretical energy consumptions.

Table 11. *Additional costs for energy consumption according to real data for 4 eBuses with 42 kWh LTO batteries from 2015 till 2026 (numbers in 1000 €)*

Year	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**
Difference cost	4.3 – 9	4.3 – 9	4.3 – 9	4.3 – 9	4.3 – 9	4.3 – 9	4.3 – 9	4.3 – 9	4.3 – 9	4.3 – 9	4.3 – 9	4.3 – 9

Thus, the results show, that accordingly to the new data about eBuses energy consumption, costs added to cash flow vary from approximately 4 300 € to 9 000 € (Table 11) each year for eBuses with 42 kWh LTO batteries. Now, assuming the worst-case scenario would be additional 9 000 € added to cash flow, the new cash flows for years 2015-2026 will look like in Table 12.

Table 12. *Cash flow for 4 eBuses with 42 kWh LTO batteries from 2015 till 2026 (numbers in 1000 €) with additional costs for energy consumption*

Year	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**
Buses	1638	100	100	100	100	100	318	100	100	100	100	100
Infra	224	4	4	4	4	4	4	4	4	4	4	4
NPV	3007											

Thus, the results show that even in the worst-case scenario according to the new Net Present Value, eBuses with 42 kWh LTO batteries will still save money in 12-year period compare to the diesel buses which is a good sign. Although, the amount of saved money will be relatively low, only around 88 000 € and the break event point will move closer to 2025, the advantage of changing the public transportation to eBuses from economic point of view is still seen. The visual representation for the cash flows with implemented results from energy consumption calculations in this work are demonstrated in Figure 28.

That is an example of how accuracy of energy consumption data collection may affect the cash flow predictions for the next years. The difference in around 0.3 kWh/km may result in raising or decreasing costs by approximately 100 000 € which may easily result in shifting the break event point to almost one year further or back dependently on different circumstances considered for cash flow calculations. The shift of the break event point can be seen after comparison of Figure 27 and Figure 28. This shows how important it is to concentrate on proper data collection.

Thus, one of the most important parts of eBuses is the battery. Dependently on the battery and its necessary replacement, cash flow for eBuses might have a significant change. Moreover, to be more precise, prices for every component essential for operating eBus, must be known, not estimated. In that case, the NPV can change to higher or lower number just because of more exact information used for the calculations.

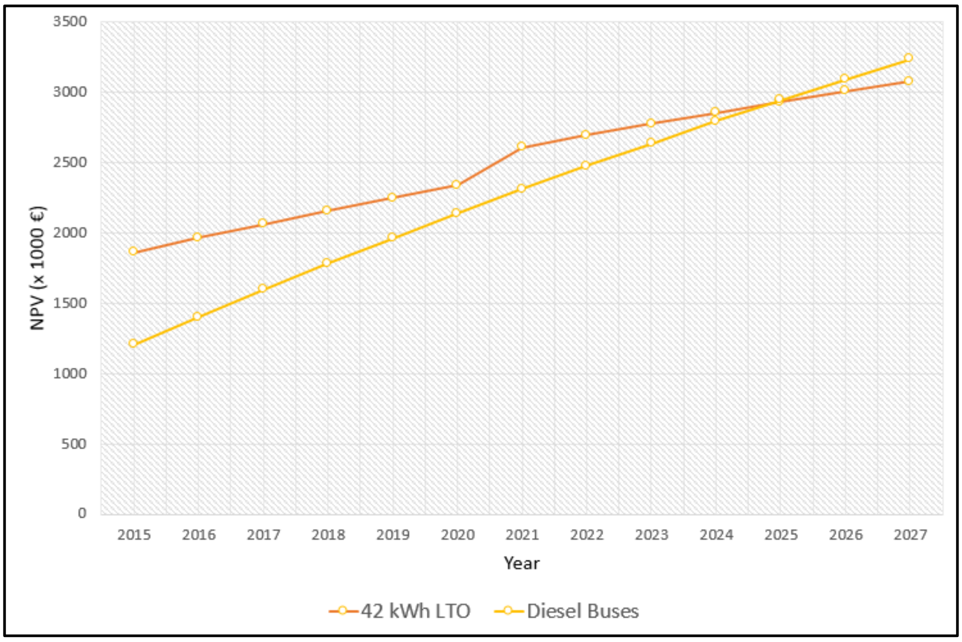


Figure 28. *Cash flows diagram for both cases after the changes in energy consumption accuracy are added*

Another point, related to energy consumption and battery use for eBuses, is that dependently on the level of energy consumed with eBus during its operation time affects the battery life cycle which affects the required time for replacement and then, the cash flow itself. Moreover, the energy consumed during routes for eBuses affects how often or how long eBuses must be charged after. That point also results in different approaches of how frequent the intermediate charging stops on the route are necessary for considered eBus.

Consequently, the energy consumption of eBuses has a significant effect on the cash flow and profitability of eBuses compared to diesel buses. Even a slight increase or decrease in energy consumption may have a significant effect on final costs of eBus and its components in a long term. However, the industries on developing eBuses are always working on newer technologies which will decrease the costs of each part necessary for proper eBuses operation. That will eventually decrease the cash flow for eBuses in few next years, and it will not be as constant as in Table 11 for example.

Calculations in [22], where comparison of the lifecycle cost structure of electric and diesel buses were also made, gave slightly different results when the life cycles of eBuses and diesel buses were compared. The calculations were made for electric and diesel buses costs according to 2017 prices in Slovakia. However, costs in that case were different for both electric and diesel buses together and accordingly to prices in Slovakia. Average electricity consumption in that case was closer to calculations made in this work. The number was 1.27 kWh/km. Thus, the difference with the real-time data considered in this work variates from -0.076 kWh/km to 0.13 kWh/km. The results in [22] gave the different break point of life cycle costs (same as cash flow). In the calculations for Slovakia case, eBuses started to save money only approximately after 17 years of operation (Figure 28).

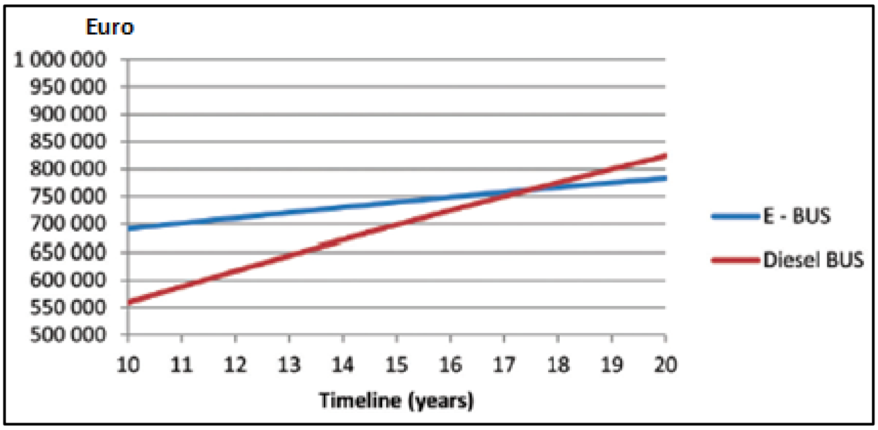


Figure 29. *Break point of compared life cycle costs of eBuses and diesel buses for 2017 Slovakia case [22]*

Thus, the information from previous researches and the results defined in this work show, that it is difficult to be exact with cash flows (life cycle costs) at the present moment, even with developing data collection of variables taken from eBuses operation. This is the consequence of still growing and, as a result, not stable industry of eBuses. Moreover, there are still factors affecting the cash flow calculations from prices of details of eBuses to average energy consumption on the same road where that bus is operating.

The energy consumption of eBuses still plays a significant role in calculations of its life cycle costs. Dependently on the energy consumption, the calculations may change the difference between cash flows for eBuses and diesel buses up to around 100 000 €. Thus, the energy consumption of eBuses is important part of costs calculations which can make a dramatic difference when calculated for several years. However, the future minimization of inaccuracy of data collection in that case will bring more stable and precise picture of advantages of eBuses compared to diesel buses in a long run.

6. THE WAYS TO IMPROVE CURRENT WORK

As one might notice, the importance of the accuracy for data collection can bring a drastic change for calculations it is applied to. It may move the break point after comparison future cash flows to one year further or back. It may result in dramatic raise or decrease of money spent on bringing eBuses instead of diesel buses. It can affect the choice of the battery for eBus or even the location of the infrastructure for eBuses.

After research completed in current work and application of the results to life-cycle costs of eBuses, this thesis work gives an idea for future development of eBuses data collection and calculations done for that. There are several ways to improve future researches or researches referring to this work.

Firstly, all the data for every value should be taken for the exact same time to be more accurate in comparison of relationships between those. If the speed of eBus is taken every second, it would bring more precise results, if the energy consumption changes of eBus would be also recorded for every second (in the provided data energy consumption status was taken for every 5 seconds). Moreover, it would give more accuracy for calculations, if, for example, energy consumption would be recorded as a change of the value between data collection times with more precise values (the accuracy in provided data was up to 0.1 kWh in that case).

Secondly, provided data had some crucial breaks for calculations of average values which should be avoided in advantage to accuracy of calculations. Figure 30 demonstrates the huge interruption during collecting the energy consumption data while bus 256 had speed 0 km/h. Considering, that energy consumption value change was almost always around 0.2 kWh, that jump in 6.5 MWh could have a huge impact on the results of calculated values. For calculations made in this work such values were filtered out.

	busId	nodeId	value	ts
524	256	528	0.000000	2018-06-01 13:40:09.000
525	256	528	0.000000	2018-06-01 13:40:14.000
526	256	528	0.000000	2018-06-01 13:40:19.000
527	256	528	0.000000	2018-06-01 13:40:24.000
528	256	528	6425.500000	2018-06-01 13:40:29.000
529	256	528	0.000000	2018-06-01 13:40:34.000
530	256	528	0.000000	2018-06-01 13:40:39.000
531	256	528	0.000000	2018-06-01 13:40:44.000
532	256	528	0.000000	2018-06-01 13:40:49.000

Figure 30. *Interruption during collecting the energy consumption data for eBus*

Thirdly, the data provided from Smart Tampere is incredibly abundant and could be used in many variations of researches. It consists almost every necessary for any calculation value. However, some values in that data were not changing or were not taken at all. For example, the number of passengers recorded for the same moment as the energy consumption could help to build the relationships between those which would result in more accurate results of energy consumption in general.

Finally, speaking of calculations in this work, another way to analyze the data of energy consumption could be with straight values without relying on average values. For example, with the cash flow calculations, instead of average energy consumption per km, the actual energy consumption from the real-time data could be applied for each year. That would increase accuracy of calculations significantly.

All these methods or improvements obviously would take time and a lot of researches to develop. Some might take only few changes, where others could take years to, for instance, record and apply. However, the future trends tend to improve all the stated above aspects and will most likely bring more accuracy for analyzing such data.

7. CONCLUSION

EBus industry grows rapidly from the prototype phase to its final replacement of current public diesel buses. Prices and details costs also change towards affordability. More and more countries start to build the necessary infrastructures which allow the usage of eBus technologies.

This thesis work was concentrated on electrical energy consumption of eBuses. The data provided from Smart Tampere allowed to observe and analyze the real-time energy consumption of 4 eBuses located in Tampere, Finland. Detailed overview of that data helped to look at influential factors of the accuracy of energy consumption and its implementation for cash flow calculations.

The results calculated in this study demonstrate energy consumption of four eBuses and recalculated cash flow for eBuses with new results for 12 years. The variability of energy consumptions of all four eBuses which were calculated in this thesis work are collected in Table 13.

Table 13. *Energy consumptions of four Tampere eBuses depending on scale*

Energy consumption	Bus 256	Bus 1855	Bus 1884	Bus 1911
Per hour, kWh/h	14.34 – 16.52	15.02 – 15.89	14.4 – 15.51	14.88 – 15.72
Per month, kWh/month	1749.56 – 4135.37	3543.17 – 4525.87	4001.93 – 4470.27	2719.97 – 4179.77
Per season, kWh/season	5248.68 – 12401.1	10629.51 – 13577.6	12005.8 – 13410.81	8159.91 – 12539.3
Per kilometer, kWh/km	0.97 – 1.8	1.09 – 1.44	1.15 – 1.23	1.12 – 1.7

It is necessary to mention, that for every calculation result stated in Table 13 and related to buses 1855, 1884 and 1911, the data was not collected for winter and spring seasons during the year. Thus, the variations of the results migh significantly differ when such data will take a place. This might be one of suggestions added to the ways of improving this work in the future and for any future researches.

Another calculation made in this thesis work is feasibility of electric buses in public transportation or simply cash flow for 12 years with the real-time based results. This calculation was based on previous research made by Olli Vilppo and Joni Markkula in 2015. The result of new calculations demonstrated the clear importance of necessity in accuracy when the electrical energy consumption data is collected, and average values are defined.

The results defined in calculations of cash flow with new values demonstrated the difference, that more precise data collection and calculations can make. With the change of average energy consumption per kilometer up to 0.3 kWh/km, the break event point between diesel buses and eBuses which shows the year, when eBuses start to save money compare to diesel buses, might move to almost one year later or one year earlier, because of the change in NPV values.

Another field where the calculations from this work can be applied is cash flow predictions for more precise values. With the knowledge of real-time based average electrical energy consumption calculations, the further calculations on feasibility of eBuses can be done more accurately. As it was mentioned earlier in this work, the more precise values for such calculations can make a dramatic change resulted in a year more or less till the break event point.

Finally, this work can be taken as the fundamental calculations for the future researches or calculations where the electrical energy consumption for eBuses is taken into consideration. Moreover, if any further calculation-based researches also consider the ways of improving current work stated in Chapter 6, the next calculations will be much closer to the reality.

In conclusion, there are a lot of studies related to eBuses electrical energy consumptions which were based on estimations. Those estimations obviously were not far from the reality, but they still were calculation-based. Such assumptions are close to actual electrical energy consumptions of eBuses. However, operating in real-life scenario eBuses have many factors which are unpredictable and depend on environment they are used. Thus, the data collection for the electrical energy consumption of eBuses is very important aspect for future development and researches. Such data can be used in many fields surrounding the proper and complete eBuses operation.

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