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ELECTRIFYING ROAD FREIGHT TRANSPORT

A comparative study in Finland and Switzerland

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ABSTRACT

Mehdi Jahangir Samet: Electrifying Road Freight Transport. A comparative study in Finland and Switzerland.

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Different low-emission mobility and green logistics strategies have been followed by the European Commission in recent years to reduce greenhouse gas (GHG) emission in the transport sector. On top of all these strategies, milestones and targets have been set for the electrification of road transport in the European roadmap. The range anxiety has been subjected as a matter of debate for electrifying different truck classes by using battery electric vehicles (BEVs). However, the technical battery and fast-charging limits will cause more challenges with the electrification of medium and heavy-duty trucks compared to the light-duty ones.

The objective of this thesis is to evaluate the potential of electrifying road freight transport by implementing the battery electric trucks (BETs) in Finland and Switzerland. For this purpose, a three-step framework is suggested to prepare data, analyse electrification potential, and estimate the emission-cost factors. The main resources for the data preparation step are the valuable freight travel datasets, which previously processed by Liimatainen et al. (2019), for Finland and Switzerland in 2016. The data preparation and electrification analysis are customised based on the battery electric vehicle potential (BEVPO) model, developed by Melliger et al. (2018), and the requirement settings in the different scenario packages of battery and fast charging facilities. Finally, the emission-cost analysis step is dedicated for evaluation of the CO_2 equivalent ($CO_{2,eq}$) life cycle assessment (LCA), total cost of ownership (TCO), and action costs for $CO_{2,eq}$ reduction potential in different electrification scenario packages.

This study shows that the road electrification potential in Finland is limited based on the current technology (with 10% tkm coverage). However, Switzerland has a larger potential for electrifying road freight (with 84% tkm coverage) maybe because of applying the smaller gross vehicle weight (GVW) policy for the road transport, having the smaller road network, and covering the larger fast charging service area. Moreover, the best scenario package is selected by considering the $CO_{2,eq}$ LCA reduction potential as well as relevant action costs for short and long-term horizons in both countries. In Switzerland, the best scenario package is based on the current technology of battery and fast charging facility which results in 56% $CO_{2,eq}$ LCA reduction (0.93 million tons $CO_{2,eq}$ per year) with the action cost of -5 €/ton $CO_{2,eq}$. The negative action costs for $CO_{2,eq}$ LCA reduction in Switzerland means that the benefits are more than the costs in the relevant electrification scenario. In Finland, the most cost-efficient electrification potential will be achieved in the short-term horizon with the help of 2,348 km electric road systems (ERSs), which results in 24% $CO_{2,eq}$ LCA reduction (0.60 million tons $CO_{2,eq}$ per year) by the action cost of 550 €/ton $CO_{2,eq}$. However, for the long-term horizon in Finland, 50% increase in the battery capacity, as well as access to ultra-fast charging facilities with 450-kW power, can lead to a better alternative, which results in 35% $CO_{2,eq}$ LCA reduction (0.87 million tons $CO_{2,eq}$ per year) by the action cost of 522 €/ton $CO_{2,eq}$. The emission and cost results in this thesis consist of high uncertainty ranges because of uncertainty ranges in the emission and cost estimation parameters. The uncertainty ranges would be reduced by using more accurate assumptions based on future research studies.

Keywords: Electrifying Road Freight Transport, Greenhouse Gas Emission, Battery Electric Vehicles, Battery Electric Trucks, Battery Electric Vehicle Potential Model, Life Cycle Assessment, Action Costs for CO_2 Equivalent Reduction, Electric Road Systems

PREFACE

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LIST OF SYMBOLS AND ABBREVIATIONS

AADT	Annual Average Daily Traffic
API	Application Program Interface
BET	Battery Electric Truck
BEV	Battery Electric Vehicle
BEVPO model	Battery Electric Vehicle Potential model
BMS	Battery Monitoring System
BNEF	Bloomberg New Energy Finance
BSS	Battery Swapping Station
CNG	Compressed Natural Gas
$CO_{2,eq}$	CO_2 equivalent
CS	Charging Station
CT	Conventional Truck
DoD	Depth of Discharging
EOL	End-of-life
ERET	Extended Range Electric Truck
EREV	Extended Range Electric Vehicle
ERS	Electric Road System
ET	Electric Truck
EV	Electric Vehicle
GHG	Greenhouse Gas
GIS	Geographic Information Systems
GVW	Gross Vehicle Weight
ICEV	Internal Combustion Engine Vehicle
kW	Kilowatt, a unit of power
kWh	Kilowatt hour, a unit of energy
LCA	Life Cycle Assessment or Life Cycle Analysis
LNG	Liquefied Natural Gas
MC	Monte Carlo

MEO-model	Multilevel Energy Optimization model
NPV	Net Present Value
NST2007	Standard goods classifications for transport statistics
OD data	Origin-destination data
OTC	One-time Cost
PHEV	Plug-in Hybrid Electric Vehicle
PLZ	Postleitzahl means “postal routing number” in Germany
PP scenario	Policy Package scenario
RC	Recurring Cost
TCO	Total Cost of Ownership
tkm	Ton-kilometre, a unit reflects freight load multiply by distance
TTW	Tank-to-wheel
V2G	Vehicle to Grid
WTT	Well-to-tank
WTW	Well-to-wheel

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1. INTRODUCTION

1.1 Background

According to Berger (2016), the transport sector has been the second-largest source of greenhouse gas (GHG) emissions during the recent years in Europe, by around 25% share of all GHG emissions. Moreover, road transport consisted up 72% of the whole GHG emissions in the transport sector (Berger 2016). Additionally, the current share of freight road transport emission is around half of the transport sector which is expected to grow for the next decades up to 70% (Mulholland et al. 2018; ITF 2017). Regarding the above figures, the decarbonisation policy of freight transport sector has been focused by the European Commission in recent years (EURELECTRIC 2017).

On the one hand, the battery electric vehicle (BEV) has been represented amongst the top three cost-efficient solutions for GHG reduction (Berger 2016). Accordingly, different targets and milestones have been set as the European roadmap for electrification of road transport (European Roadmap 2017). The potential of GHG emission reduction by using BEVs can be improved if the sources of the grid electricity generation are clean (Van Vliet et al. 2011). However, the range anxiety has been accounted for the main issue with the adoption of BEVs (Melliger et al. 2018). The current limitation of battery and charging technology has a direct impact on the range anxiety. Melliger et al. (2018) introduced a battery electric vehicle potential (BEVPO) model to estimate the potential of road electrification based on different scenario packages of BEV models and fast charging facilities. The BEVPO model is an object-oriented Java program which utilises an accurate methodology for route assignment via online service of google map application program interface (API).

On the other hand, the range anxiety issue associated with the medium and heavy-duty is more challenging compare to light-duty EVs (Liimatainen et al. 2019). Developing the BEVPO model to estimate the potential of electrifying road freight transport can lead to more accurate results. However, according to Liimatainen et al. (2019), the range anxiety issue for electrifying road freight transport is intensified by the current battery technology and charging facilities limits. Moreover, the wider range of energy consumptions for different truck weight classes makes the data modelling and analysis more challenging by the BEVPO model.

Furthermore, the results of BEVPO model need to be analysed in terms of the cost and CO_2 emission. Therefore, the results can be evaluated through the total cost of ownership (TCO) for cost, and life cycle assessment (LCA) for CO_2 equivalent ($CO_{2,eq}$) emission (Huismans 2018). Finally, the most cost-efficient alternative solutions can be selected based on the $CO_{2,eq}$ abatement costs measure (Berger 2016).

1.2 Objective and research questions

Based on the knowledge gaps in the road freight transport context, the main objective of this thesis…

> *…is to estimate the potential of electrifying the road freight transport by implementing the battery electric trucks (BETs) in Finland and Switzerland.*

Accordingly, the main objective is formulated in threefold: (1) to evaluate the impact of range limitations and developments on the potential of electrifying the road freight transport by using battery electric trucks (BETs) in Finland and Switzerland, (2) to estimate the $CO_{2,eq}$ reduction potential of electrifying the road freight transport by using the battery electric trucks (BETs) in Finland and Switzerland, and (3) to estimate the economic viability impact of electrifying the road freight transport by using the battery electric trucks (BETs) in Finland and Switzerland. Therefore, the following three main research questions with accompanying sub-research questions can be proposed:

- **Main research question 1:** What are the potentials of electrifying road freight transport by using BETs in Finland and Switzerland based on improvements of battery, and fast charging technologies?

1. What share of road freight trips can be successfully covered with the currently available BETs models and the current charging infrastructures in Finland and Switzerland?
2. How much the improvement of BETs range and charging infrastructure can raise the share of successful BETs trips in Finland and Switzerland?
3. What other alternative or/and complementary solutions could be proposed for the electrifying road freight in Finland and Switzerland?
4. What are the road freight transport range needs in Finland and Switzerland?

- **Main research question 2:** What could be the $CO_{2,eq}$ reduction potentials in Finland and Switzerland using life cycle assessment (LCA) approach?

1. What could be the amount of $CO_{2,eq}$ well-to-wheel (WTW) emissions in different scenario packages of battery and charging infrastructures in BETs in Finland and Switzerland? And how does it compare to the conventional diesel truck?
2. What could be the amount of $CO_{2,eq}$ emissions aside from WTW emissions in different scenario packages of battery and charging infrastructures in BETs in Finland and Switzerland? And how does it compare to the conventional diesel truck?

- **Main research question 3:** What could be the total cost of ownership (TCO) in BETs for different scenario packages of battery technology and charging infrastructures compared to the TCO of the diesel conventional trucks (CTs) in Finland and Switzerland?
    1. What could be the action costs for $CO_{2,eq}$ reduction in different scenario packages of battery and charging infrastructures in BETs in Finland and Switzerland?
    2. What could be the best scenario packages, in terms of potential $CO_{2,eq}$ reduction and action costs for short and long-term horizons, of battery and charging infrastructures in BETs in Finland and Switzerland?

The comparative analysis of road freight electrification in Finland and Switzerland can be interesting because of the diversity of regional conditions. For instance, they have different levels of electrifying infrastructure, different legislation limits for the maximum freight load in road transport, different road network sizes, and freight transport demand. Therefore, the results of this thesis may be utilized for other countries with similar regional conditions.

1.3 Scope of study

This thesis will focus on understanding the electrification potential of road freight transport in Finland and Switzerland. The study is defined in continuation of previous research by Liimatainen et al. (2019), and the boundary is based on the available travel freight survey data for the medium and heavy-duty trucks (with gross vehicle weight more than 3.5 tons) in Finland and Switzerland in 2016.

The generic aspects of different alternative solutions for electrification road freight will be reviewed. However, the research mainly focuses on the evaluation of electrifying road freight transport based on battery and fast charging technology improvement scenarios in Finland and Switzerland. The $CO_{2,eq}$ emissions will be evaluated as the life cycle assessment (LCA) concept. However, other emissions like NO_x will not be evaluated.

Moreover, to evaluate the economic viability of electrifying road freight transport, the total cost of ownership (TCO) will be used. Different cost elements such as one-time cost (OTC) and recurring cost (RC) are calculated based on the limited available literature on this topic.

Since the cost and emission elements represented in the literature have been varied to some extent, the uncertainty level in cost and emission analysis is high. Therefore, some sensitivity analyses aim to evaluate the uncertainty impact of different variables on the final cost and emission results.

1.4 Overview of the research methods

As it is described in the objective of this thesis, the threefold of objectives are (1) evaluate the impact of range limits and developments on the potential of electrifying the road freight transport by using BETs in Finland and Switzerland, (2) estimate the $CO_{2,eq}$ reduction potential of electrifying the road freight transport by using the BETs in Finland and Switzerland, and (3) estimate the economic viability impact of electrifying the road freight transport by using the BETs in Finland and Switzerland.

The methods in this thesis will be described exclusively in Chapter 3 and 4. In this section, the general research approaches are described shortly according to the relevant references. There might be different definitions for the term of research, however, their bottom line can be concluded as systematic studies due to achieve useful knowledge concerning specific topics. Different research topics may require their specific research methods (e.g. management accounting (Jönsson and Lukka 2006), health and social care (Winter and Munn 2001), and management (Gummesson 1993))

According to the “research onion" described by Saunders et al. (2019), there are eight main research strategies in the business domain such as experiment, survey, archival research, case study, ethnography, action research, ground theory, and narrative inquiry. However, this thesis mainly focuses on transport and spatial analysis methodology and techniques. Therefore, according to Haining (2009), different computation and visualization techniques for the spatial analysis on a network can be discussed through three different stages of conceptualisation (for generating the model of the real world by using field and object views), representation (for generating the basic model of the spatial data matrix by using points, lines, and polygons), and observation & measurement (for generating a complete model of the spatial data matrix by using space, time, attribute data, and connectivity matrix). Moreover, Allen et al. (2012) represented survey techniques such as driver and vehicle trip survey in freight transport studies. In terms of data analysis, Książkiewicz (2012) also discussed different quantitative and qualitative research methods' applications in transport planning based on spatial perspectives.

Regarding the research strategies of the "research onion" (Saunders et al. 2019), the research conducted in this thesis is the result of the combination of experiment, archival research, and case study strategies. Moreover, the travel survey data results of the previous freight transport research are used for the data analysis procedures.

For the data analysis procedures, quantitative research methods such as simulation and spatial data analysis are implemented by the following experimental software models and tools. The data analysis procedure includes Java programming for using the BEVPO model, and R programming for summarizing the results and providing geospatial transportation planning and analysis. For generating the map visualizations, python programming in ArcGIS, as well as R programming, are implemented.

1.5 Structure of the thesis

In this thesis, the theoretical background for electrifying alternative solutions will be reviewed in Chapter 2. In Chapter 3, the battery electric vehicle potential (BEVPO) model, according to Melliger et al. (2018), will be extended to be used as an analytical tool to evaluate the potential of electrifying road freight by the implementation of different scenario packages for the BETs and the relevant fast charging facilities. Furthermore, the main framework for the application of BEVPO model for evaluation of electrifying road freight transport will be represented in this Chapter.

In Chapter 4, based on the given framework and the theoretical background in Chapter 3, the life cycle assessment (LCA) and total cost of ownership (TCO) will be formulated for the different scenario packages of the BETs. In Chapter 5, the results of BEVPO model analysis for different scenario packages in Finland and Switzerland will be evaluated. Accordingly, the relevant LCA and TCO of different scenario packages will be analysed. Finally, the best alternative solution will be represented based on cost-efficiency measures such as the action costs for the LCA reduction potential for different horizons.

2. THEORETICAL BACKGROUND FOR ELECTRIFYING ALTERNATIVE SOLUTIONS

According to multiple resources (Van Vliet et al. 2011; Onat et al. 2015; Kawamoto et al. 2019), the battery electric vehicles (BEVs) solutions associate with electricity power generated from low-emission sources can be a prominent option to tackle the greenhouse gas (GHG) emission issue resulted from the ever-increasing daily use of the internal combustion engine vehicles (ICEVs). However, there are many factors involved in the trade-off between the BEVs and ICEVs. For instance, the carbon-footprint level of the electricity mix generation sources used for charging the BEVs has a great impact on such trade-off result (Van Vliet et al. 2011). Moreover, the range anxiety due to the shorter-range possibility in BEVs, compared to the conventional vehicles, as well as the limited access to the fast charging facilities can have a direct impact on the decision made by the buyers (Melliger et al. 2018).

The similar logic can be used for the adoption of battery electric trucks (BETs) to reduce the potential GHG of road freight transport. Due to the ever-increasing share of freight transport from the total emissions in the transport sector, which is currently accounted around half of the total emissions from the transport sector and expected to grow up to 70% in the next decade (Mulholland et al. 2018; ITF 2017), the BETs can be a potential greener transport mode compared to the conventional trucks (CTs). Although the potential impact of utilizing the BETs may be high, the relevant technical and economic barriers of using BETs for the long-haul and heavy freight transport purposes are challenging (Mareev et al. 2018; Liimatainen et al. 2019).

The first following section aims to review the results of the most relevant research studies to the thesis's topic. The next two following sections aim to discuss more details of the barriers and solutions for using the BETs and fast charging facilities. In addition, the last three following sections are dedicated to discussing the other alternative solutions for the adoption of BETs such as Range-extended technology in EVs, electric road systems (ERSs), and battery-swapping technology.

2.1 Review the relevant research studies

Very limited resources can be found focusing on the lifecycle cost and emission analysis of the electrification road freight transport by considering fast charging facilities. The research studies conducted by Huismans (2018) and Mareev et al. (2018), in addition to

Liimatainen et al. (2019), are found as the most relevant research studies to this thesis' topic. The following paragraphs will reflect summary results of these research studies.

Liimatainen et al. (2019) analysed the potential of electrifying road freight by considering the fast charging facilities in Finland and Switzerland. They processed freight travel surveys for trucks with the gross vehicle weight (GVW) of more than 3.5 tons in 2016 in both countries. They analysed 4 different electrification scenarios such as current technology, improved vehicles, improved vehicles and charging, and towards full electrification. The following assumptions are considered for these scenarios. First, the battery capacities varied from 150 to 350 kWh and 400 to 800 kWh for rigid and articulated trucks, respectively. Second, the gravimetric density of batteries varied from 120 to 360 Wh/kg. Third, overnight charging power for 8 hours varied from 50 to 150 kW. Finally, the on-road recharging power for 2 hours varied from 50 to 400 kW. The results reflected that 71% and 35% of road freight transport in tonne-kilometres may be electrified by using battery electric trucks in Switzerland and Finland, respectively. However, in terms of emission and cost analysis, they only evaluated the direct emission of diesel fuel.

Huismans (2018) claimed that the reduction potential of $CO_{2,eq}$ life cycle assessment (LCA) by implementing the electric tractor-trailer could be varied from 34 to 41%. The market entrance and traffic growth were modelled for estimating the reduction potential of $CO_{2,eq}$ LCA. However, the range needs in Netherland were evaluated only based on four sample routes and summary freight measures such as average haulage. Huismans (2018) also analysed the total cost of ownership (TCO) of the tractor-trailer's electrification for 2018, 2020 and 2030. The results showed that the electrification of tractor-trailers, relied on the fast charging facilities, were not viable compared to conventional trucks because of the high cost of the battery. However, if the cost of the battery reduces to less than 200 €/kWh and the battery performance increases from 3,000 cycles to 6,000 cycles (equivalent for 4 years battery lifetime), the relevant electrification scenario will turn into an economically viable option.

Mareev et al. (2018) evaluated the required battery capacity of BETs for the long-haul transportation in Germany. They claimed that the average range needs, equivalent for 4.5 hours daily trip duration, for long-haul transport by heavy-duty BETs with gross vehicle weight (GVW) of 40 tons (payload of 17.5 tons) in the main German highways will be responded by the battery capacity of 825 kWh. They also concluded that the total life cycle costs in BETs can be at the same level of the diesel CTs, for example, if the battery pack costs of 145 €/kWh and 7 years battery lifetime are assumed. In this study, the total mileage of 939,600 km and 895,800 km were analysed for the average and heavy route scenarios, respectively.

Regarding the above information, the following defects can be summarised based on the previous researches. First, the impact of the range anxiety, based on travel survey data and practical route assignments, was neglected in the results. Second, except to Liimatainen et al. (2019), the scopes of the researches were limited to the heavy-duty BETs with maximum of 40 tons GVW. Finally, the action costs for $CO_{2,eq}$ reduction were not evaluated.

2.2 Battery and range technology limitation

The BETs are a questionable alternative for the replacement of heavy-duty CTs since a higher energy consumption and lower energy density of battery in this truck class are required compared to the light-duty trucks (Den Boer et al. 2013). Therefore, BETs are a more competitive and viable option for medium-duty CTs replacement. According to multiple resources (Davis and Figliozzi 2013; Feng and Figliozzi 2013; Lee et al. 2013), under certain circumstances, the BETs can be competitive alternatives for the medium-duty conventional trucks, the class 4-6 with relevant payload capacities of 2-8 tons, based on LCA and TCO measures.

Hopefully, due to the possible improvement of battery characteristics as well as the reduction of the battery price in the close future, the BETs can be a more viable alternative for heavy-duty CTs (Sen et al. 2017; Mareev et al. 2018; Ambel et al. 2017). The currently available technology of heavy-duty BETs for the long-haul freight transport purpose can be varied by brands. However, the maximum range of some commercial models may reach up to 300 km for payload capacities around 30 tons (Appendix A: truck model class 8-day cab produced by BYD).

There are models with longer ranges such as Tesla truck model Semi 800, which can carry lower payloads around 20 tons. Appendix A represents a full list of all BET models for 4-8 classes which range from 2 to 30 tons for payload capacities. Some of these models have been failed as commercial products due to marketing and technical issues.

The payload capacity limits of heavy-duty BETs are concerned with the total gross vehicle weight (GVW) limitation in road transports and the gravimetric energy density of the battery (Mareev et al. 2018). Moreover, different factors such as the environment temperature, discharging current rate, charging rate, depth of discharging (DoD), and the time interval between full charge cycles have an impact on the performance of the battery used in BEVs (Wenzl et al. 2005; Vetter et al. 2005).

In addition, the battery behaviour, related to the thermal runaway inside the battery cells, get affected by the chemistry, material science, and heat transfer. As a result, any errors happening in these factors can lead to a safety problem. All in all, the technical limits mentioned above would justify the current limits for the battery technology design and production in terms of size, weight, and capacity (Rezvanizaniani et al. 2014).

2.3 Fast charging technology and limitation

Chargers can be divided into four different types of slow, rapid, fast and ultra-fast charger. Each charger type has its characteristics based on the chemistry, the C rate which means the rate of charge and discharge, the charging power, the time, the temperature, and the charge termination. Table 1 represents the characteristics of different charger types (Battery University 2019).

Regarding the table, the slow chargers may not be a viable charger type for the larger battery capacities requirements of the long-haul heavy-duty electric trucks (Huismans 2018). It cannot fulfil the time limitation requirement even for overnight charging of heavy-duty electric trucks (Mareev et al. 2018).

Table 1. *Charger and battery characteristics (Battery University 2019).*

Type	Chemistry	C rate	Power	Time	Temperatures	Charge termination
Slow charger	NiCd Lead acid	0.1C	Less than 7 kW	14h	0ºC to 45ºC (32ºF to 113ºF)	Continuous low charge or fixed timer. Subject to overcharge. Remove battery when charged.
Rapid charger	NiCd, NiMH, Li-ion	0.3-0.5C	7-22 kW	3-6h	10ºC to 45ºC (50ºF to 113ºF)	Senses battery by voltage, current, temperature and time-out timer.
Fast charger	NiCd, NiMH, Li-ion	1C	~50 kW	1h+	10ºC to 45ºC (50ºF to 113ºF)	Same as a rapid charger with faster service.
Ultra-fast charger	Li-ion, NiCd, NiMH	1-10C	100-450 kW	10-60 minutes	10ºC to 45ºC (50ºF to 113ºF)	Applies ultra-fast charge to 70% SoC (State of Charge); limited to specialty batteries.

The rapid and fast charger types can be available for different EVs types, while, the ultra-fast chargers are customized only for specific EV brands such as Tesla. The charging time can be a function of the battery design, chemistry, voltage, current, and temperature. The design of ultra-fast chargers can be more complicated, and their settings need to be specified based on the designed battery cells to control the safety and the life cycle. The battery monitoring systems (BMSs) can be essential to improve the battery lifetime (Battery University 2019).

Even though the ultra-fast charger can be very time-efficient, they have some drawbacks. Using frequently the ultra-fast charging can reduce the lifetime of the battery in the BEVs. It is suggested to use the ultra-fast charging when it is necessary. The chemical damage procedure can be explained by the lithium deposition in li-ion battery types (Battery University 2019). The li-ion battery types are known as the best option for using in EVs because of their characteristics such as the high gravimetric energy density (Briec and Müller 2014).

The lithium deposition increases the risk of self-discharge, and subsequently, reduces the age of battery cells. Moreover, some of the environmental conditions may increase the risk of lithium deposition. For instance, the ultra-fast charging in lower temperatures increases the risk of lithium deposition. Finally, the ultra-fast charging requires high electricity power and leads to rising electricity consumptions (Battery University 2019).

2.4 Range-extended technology in BEVs

Range-extended technologies such as extended range electric vehicle (EREV) and plug-in hybrid electric vehicle (PHEV) leverage the energy density of fossil fuels such as gasoline, compressed natural gas (CNG), and diesel to solve the problem of range anxiety for adopting BEVs (Tuttle and Baldick 2012).

On the one hand, the refuelling infrastructure can provide the possibilities of longer trips. On the other hand, the fuel backup allows reducing the battery capacity compared to BEVs (Tuttle and Baldick 2012). Therefore, such downsizing of battery capacity in the range-extended technology can result in the improvement of LCA and TCO compare to the full BEVs (Onat et al. 2015).

In addition, the electric range can vary based on different parameters such as driving habits, terrain, and weather conditions. Smart energy management control systems can leverage the dynamic change of such variables to reduce the total energy consumption. Through the powertrain configuration and the power flow optimization in EREV, the energy consumption level can be reduced up to 28% in EVs (Xi et al. 2017; Kou et al. 2015).

As it is discussed earlier in Section 2.1 and 2.2, due to the larger energy consumption measures per km in electric delivery trucks, the range anxiety will increase respectively. Regarding the limitation in battery technology and the fast charging facilities in electric trucks (ETs), the range-extended technology can be a competitive alternative solution for increasing the range compared to the lighter EVs. The extended range technology can be designed to meet the customer needs (Seyam 2011; EMOSS 2020).

Zhao et al. (2016) studied the economic and $CO_{2,eq}$ LCA of electric delivery trucks. The results show that the extended range electric trucks (ERETs) and battery electric trucks (BETs) are very close to each other in terms of potential GHG reduction compared to conventional trucks (CTs). Moreover, they concluded that the BETs are a more profitable alternative compare to ERETs in terms of vehicle to grid (V2G) service revenue (Zhao et al. 2016).

All in all, the range-extended technologies could be amongst the viable alternative solutions which help to reduce the range anxiety for the adoption of BEVs for freight transport. Companies such as EMOSS have offered no limited range BETs, by using the cleaner range extenders based on the fuel types such as CNG, which can be customized according to the customer's range needs (EMOSS 2020).

2.5 Electric Road Systems (ERSs)

Electric road systems (ERSs) can be an alternative solution for the high battery capacity issue. ERSs are divided into three categories of overhead line, rail, and conductive. All these technologies make possible the longer travel trips with lower battery capacity for EVs. However, in both inductive or conductive power ERSs, complementary tools and devices, such as connecting arms, must be installed on the EVs to transfer the electricity between ERS infrastructure and EVs (Chen et al. 2015).

On the one hand, according to multiple resources (Zhao et al. 2018; Domingues et al. 2018), the investment cost and benefits in running ERSs can be high. The cost investment can be only justified through high scale demand of EVs using the ERSs. To justify the cost investment, the action costs for potential GHG reduction, defined as the benefits, can be analysed. On the other hand, the electrification scenario for promoting the heavy-duty electric trucks in long-haul applications, requires supplementary solutions like ERSs to extend the range requirements (Zhao et al. 2018; Domingues et al. 2018).

In Norway, 200 km road were analysed for two ERSs alternatives construction. The road coverage by the infrastructure in both alternative assumed to be 33%. The cost was estimated in a range from 1.16 to 1.6 and from 1.6 to 2.32 million euro per km for overhead line and rail alternatives infrastructure, respectively. The battery capacity for BET was assumed to be 320 kWh. According to the given assumption, the life cycle analysis (LCA) was applied by 2% annual traffic growth rate. After that, the cost-benefit analysis was applied by evaluating the socio-economic profitability of ERS' construction (Langhelle et al. 2018).

The results show that the break-even point of annual average daily traffic (AADT) for socio-economically profitability vary from 600 to 900 and from 600 to 1,200 for overhead line and rail alternatives infrastructure, respectively, in Norway. The action costs for CO2 reduction was also calculated as 15.5 and 34.6 €/ton CO2 reduction for overhead line alternative in 500 AADT for new road and existing road construction items, respectively (Langhelle et al. 2018).

Some other case studies were conducted to evaluate ERSs in Denmark and Sweden. In Sweden, diesel, ERS, BEV, and liquefied natural gas (LNG) were compared in terms of economy, environment, energy and resources, and operational aspects for long-haul trucks. The results show that BEV with ERS, overhead line alternative, can be a better economical alternative compare to full BEV without ERS (Gustavsson et al. 2019). In Denmark, large batteries, overhead electric road, road bound inductive, and road bound conductive alternatives were analysed for all Danish road transport. The result show that the yearly social costs of the large batteries is more than all other scenarios (Domingues et al. 2018).

2.6 Battery-swapping technology

Battery-swapping technology can solve the range anxiety issue for EVs adoption in a cost-efficiently manner. The primary idea of battery-swapping concepts for EVs comes from the early 1900s by Hartford Electric. The battery-swapping technology has been evolved by using robotic arms to exchange the depleted batteries with the full-charge ones. The battery swapping stations (BSSs) can be customized for either light or heavy-duty BEVs (Ban et al. 2019).

For the light-duty BEVs, the battery-swapping operation is done through the bottom of the vehicle, while, for the heavy-duty BEVs, the whole operation can be done through the side-swapping method. Surprisingly, the whole battery swapping operation can only take a few minutes. State Grid illustrated a six-step battery-swapping procedure for an electric truck which takes only 4 minutes (Ban et al. 2019).

According to Ban et al. (2019), BSS can be beneficial in different aspects. From the BEV local management's perspective, the BSS is subjected to fewer limitations of power-grids by local administrations compared to the fast charging station. Moreover, due to the dynamic schedule of power-grid, the charging costs can be minimised. In addition, the centralized charging station can optimize more cost elements for the battery-swapping procedure. Finally, the environmental issues related to battery waste can be managed through BSSs by implementing complementary solutions such as battery reuse and recycle.

From the customer’s perspective, the BSS can save time, since it is faster than fast charging methods and can be as fast as refuelling in conventional cars. Moreover, the customers can save money through the leasing of battery or vehicle company. The customers do not need to pay for the battery, instead, they only pay the annual charge for the battery services (Ban et al. 2019).

Although, the BSS option may theoretically have more advantages compare to charging station (CS). Running a successful BSS requires professional companies who are experts in making profits from battery services. The story of the Better Place's downfall in 2012 notifies the risk of investment in BSS due to slow market growth. Running BSS services needs high capital costs which can turn into an unprofitable business if the market demands are low (Ban et al. 2019).

Regarding the literature, the BSS challenges were discussed in details of resource planning and route assignment problems for the logistics companies who have control over the transportation business (Yang et al. 2015; Wang et al. 2017). On the contrary, the BSS impact can be analysed on a larger scale such as on a national scale for planning the power grid infrastructures. Çabukoglu et al. (2018) conducted a study on a national level in Switzerland, to evaluate the impact of battery-swapping technology on different measures such as CO_2 emission reduction and power grid raise demand potential. However, the study lacks cost analysis (Çabukoglu et al. 2018).

3. BEVPO MODEL APPLICATION FOR BETS

This chapter aims to provide a methodology to estimate the potential of the electrifying road freight transport. The battery electric vehicle potential (BEVPO) model will be described to estimate the potential of BEVs (Melliger et al. 2018). After that, a comprehensive three-step framework will be represented to evaluate the potential of electrifying road freight transport.

3.1 BEVPO model

Melliger et al. (2018) conducted a research study on range anxiety of battery electric vehicles (BEVs) adoption based on real travel demand data in Switzerland and Finland. They developed battery electric vehicle potential (BEVPO) model as an object-oriented Java model to evaluate the potential of BEVs to cover the sample survey data from both countries in 2016 (BEVPO 2018).

The research aimed to answer three main research questions. First, what range is needed for car users? Second, what share of car trips can be converted successfully based on the available battery technology and charging facilities? Finally, how much the success rate can be improved regarding battery technology and charging facility improvements.

The model could evaluate the success rate of BEVs coverage based on different assumptions such as charging activities, charging facilities, range, and route assignment. Different scenarios were defined to consider different charging facilities and road freight transport policy's impact on the BEVs' trip coverage.

Regarding the results of Melliger et al. (2018), the BEVPO model can contribute to an accurate estimation tool for future adoption of BEVs. The model applies individual route assignment based on Google API direct web service. As a result, the data analytics can be very accurate for each travel simulation procedure. The following paragraphs would discuss the BEVPO model structure and its input variables.

BEVPO model was defined as a flexible model which can be applied for different countries' datasets. It also can integrate different scenarios of car model choice, policy packages for roadway charging facilities. The model consists of four main steps for (1) data preparation, (2) geo-routing individual daily trips and sub-trips (legs) and inserting on-road charging facilities, (3) random charging stations and vehicle model assignments for each car trip, and (4) representing car trip simulation results based on all passing legs and charging activities at stations. The procedure consists of random BEV model selection, simulating the trip according to travel survey, and charging facilities at home, work, and roadways. Figure 1 illustrates four main steps of BEVPO model.

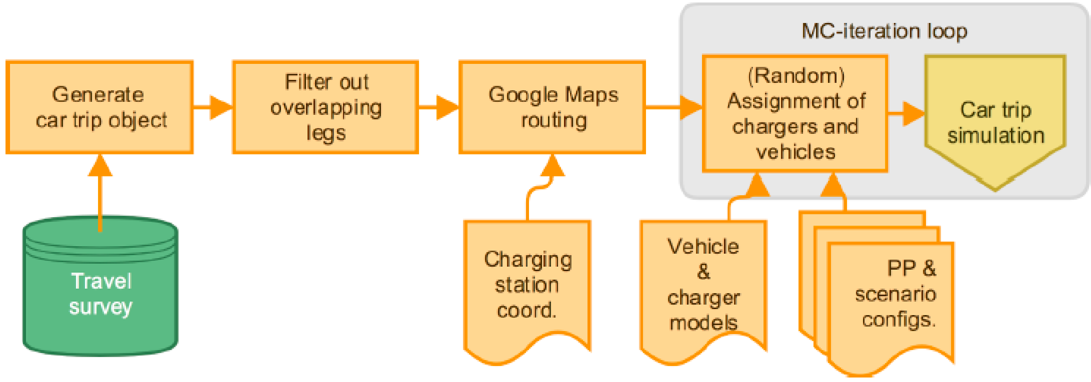


Figure 1. *BEVPO inputs and steps (Melliger et al. 2018).*

Regarding the figure, the inputs are the travel survey, fast charging facilities' coordination, charging and vehicle models, market share and policy packages (PPs) scenarios. The picture also shows in the third step, Monte Carlo (MC)-iteration loop which consists of a MC approach assigning random variation of the vehicle and charging facilities for the simulation procedure. In order to better understand the BEVPO model, the steps will be explained in the following paragraphs

In the first step, travel survey data are analysed to generate leg-data file including variables such as trip purposes, trip travel times, origin and the destination address for individual legs, car, household, and person unique IDs. It is important to notice that the trips are considered as daily trips including multiple legs with different trip purposes, and routes. The more details of input data variable formats are available in the readme file of BEVPO model which would be discussed in the next sections. However, in short, BEVPO generates car trip objects based on different individual legs of each unique household ids. The model also applies some data filtering tasks to avoid legs' duplication.

In the second step, the geo-routing assignment would be done via Google map direct API web-service. The service of Google map API is limited for free usage which varies for different Google map API applications via an API key for each user (Google API key 2020). The service can have an extra charge if the service requests exceed from the limitations. At this stage, the charging stations are connected as new legs to the route assignment of each trip by using such API service. The inserting charging station into routes depends on the search radius defined for roadway charging activities. The closer distances like 100 meters mean the fewer efforts to find charging facilities by drivers.

In the third step, the BEVPO model randomly assign stations between legs according to MC-iteration, random distributions defined for each scenario, and charging activities.

Finally, in the fourth step, a car trip is simulated based on the charging activities and energy consumption (loss) calculations. The charging activities are calculated based on the charging times, and the power of charging stations. The charging activities can be calculated by the following formula.

$$\Delta E_{charging} = P_{charger} . \Delta T \Leftarrow E_{battery} \quad (1)$$

Which $\Delta E_{charging}$ is the energy uptake in kWh within ΔT charging activity duration in hours, and the $P_{charger}$ as the power of charging facilities in kW. Moreover, the charging loss is calculated through the following formula:

$$\Delta E_{uncharging} = EC . \Delta D \quad (2)$$

Which $\Delta E_{uncharging}$ is the energy loss in kWh according to ΔD driving distance in km covered by a random BEV with an energy consumption of EC in kWh/km. Simulation procedure implements on each car trip and apply charging activities based on the given formulas and random variables. As a result, the ran-out failure would be reported if the available charge of BEV ($\Delta E_{uncharging}$) is less than the total energy required for the whole trip. The model also can provide exclusive reports of charging activities and route length coverage for the failed trips.

3.2 A framework for application of BEVPO model in road freight transport

The idea of using BEVPO model for evaluating the potential of electrifying road freight transport can be challenging in different aspects. First, the different freight truck models have a wider range of energy consumption per kilometres for medium and heavy-duty BETs compared to the light-duty BEVs. In order to solve this issue, the simulation procedure of BETs can be divided into sub-categories based on energy consumption. Second, due to the current battery, and fast charging technology limits, which is discussed in Chapter 2, long-haul trips by some heavy-duty BETs is not yet feasible. As a result, future improvement of battery technology for heavy-duty BEVs are estimated via extrapolation of light and medium-duty BEVs based on their payload capacities.

Third, the limited range, or the higher energy loss in the medium and heavy-duty BETs, increase the need to the on-road fast charging facilities. Since frequently using the fast charging facilities has its own drawbacks, therefore, other possible electrification scenarios such as the electric road systems (ERSs) can be considered as the alternative solutions in some routes. Accordingly, Figure 2 represents the thesis's framework for analysing the potential of electrifying road freight transport by using the BEVPO model as well as the relevant emission-cost impacts.

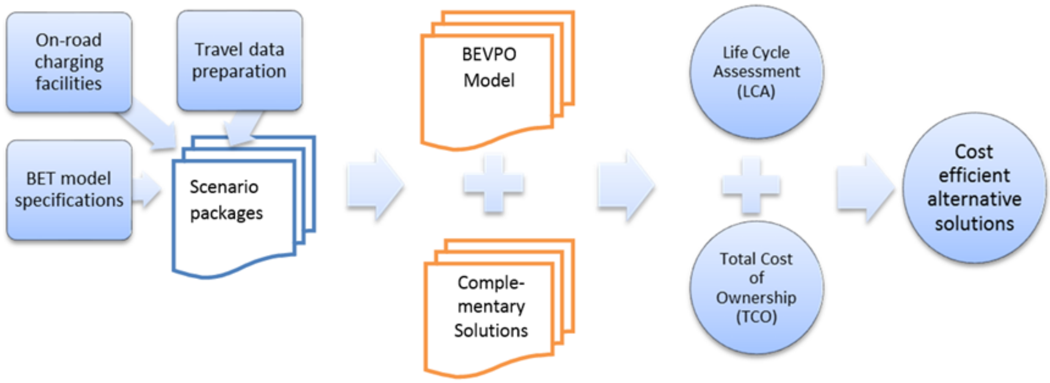


Figure 2. *The thesis's framework for analysing the potential of electrifying road freight transport by using the BEVPO model and emission-cost analysis.*

The figure shows a 3-step framework to evaluate the electrification potential of road freight transport by medium and heavy-duty trucks (with GVW more than 3.5 tons). The first step is for data preparation which consists of 4 different stages like (1) the on-road charging facilities, (2) travel data preparation, (3) BETs specifications, and (4) the scenario packages. Accordingly, more details will be discussed in the following sections in this chapter.

The second step is for electrification analysis which aimed to run the BEVPO model for different scenario packages as well as other complementary solutions. The basic methodology of this step has been introduced in Section 3.1, but the advance discussions will be provided in Chapter 5.

The third step is dedicated to the emission-cost analysis of the results from the previous steps. The relevant methodology for estimation of life cycle assessment (LCA) and total cost of ownership (TCO) in different scenarios will be described in Chapter 4. Moreover, the relevant results and analyses will be discussed in Chapter 5. Finally, the best alternative solution in each country will be selected based on the cost efficiency measures. The relevant methodology will be described in Section 4.4 in Chapter 4. In addition, the relevant discussions and analyses will be represented in Section 5.5 in Chapter 5.

3.2.1 On-road charging facilities

Based on the instruction of using BEVPO model for different countries, which is available in the GitHub account, the roadway charging station coordinates must be defined in a proper format to be readable by the model. Charging stations should be collected in a

“.csv” format with the following fields (1) “ID” which reflect a unique identifier for each station, (2) “Lat”, (3) “Lng” which reflect latitude and longitude of charging station, (4) “Power” which shows the charging station’s power in kW, (5) “Name” which refers to the name of charging stations, and finally(6) “Type” which refers to the availability status of charging station.

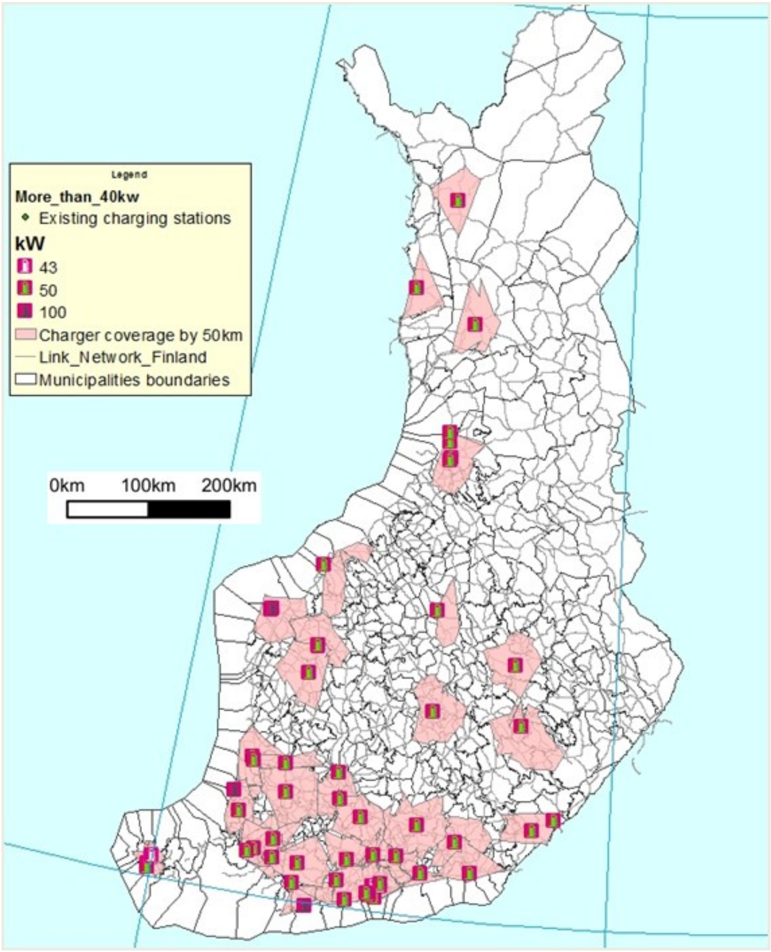
The file of charging station coordinates is defined for geo-routing assignment purposes. For each country region, specified charging station coordinates must be defined as the basic inputs. Moreover, in order to define different charging scenarios, two other inputs must be defined for charging activities assignments in the simulation procedure.

First, charging station type should be defined based on the requirements in different scenarios which can be specified by variables such as (1) “chargerID” which is a unique identifier for each charger technology types, (2) “chargerType” which describes the power characteristics of the charger in a string format, (3) “chargerPower” which refers to the power of charger in kW.

Second, a charger matrix must be defined for different simulation scenarios. This file specifies the charging technology relevant to each travel purposes by using probability distributions. For example, the home purpose can be defined to have the charging possibility by 50% with 50 kW, and 50% with 120 kW charging technology.

Regarding the criterion discussed in the charging station coordinates, charging station type, and charger matrix, the data was collected from different online sources for Finland and Switzerland. There are some specific considerations for each country which will be discussed in following paragraphs. In order to better understand the geospatial distribution of the charging stations all over the road network, ArcGIS network analysis tool is applied for the visualization of charging service area coverage in both countries. Figure 2 and Table 2 illustrate the charging service area coverage of on-road fast-charging stations in Finland and Switzerland.

The figure shows the service area coverage of 50 km from existing charging station coordinates in both countries by pink polygons. The assumption of 50 km for the main road networks can be interpreted as 50 km range for the BEV remaining to the fast charging station in the map. In other words, full coverage of network by 50 km charging service polygons would increase the chance of successful trips by relying on the on-road fast charging activities. The network analysis for service area coverage is done by filtering main road types such as the motorway, primary, secondary, tertiary, and trunk. General scheme of the maps reflects that the distribution of charging stations in Switzerland is better than in Finland.



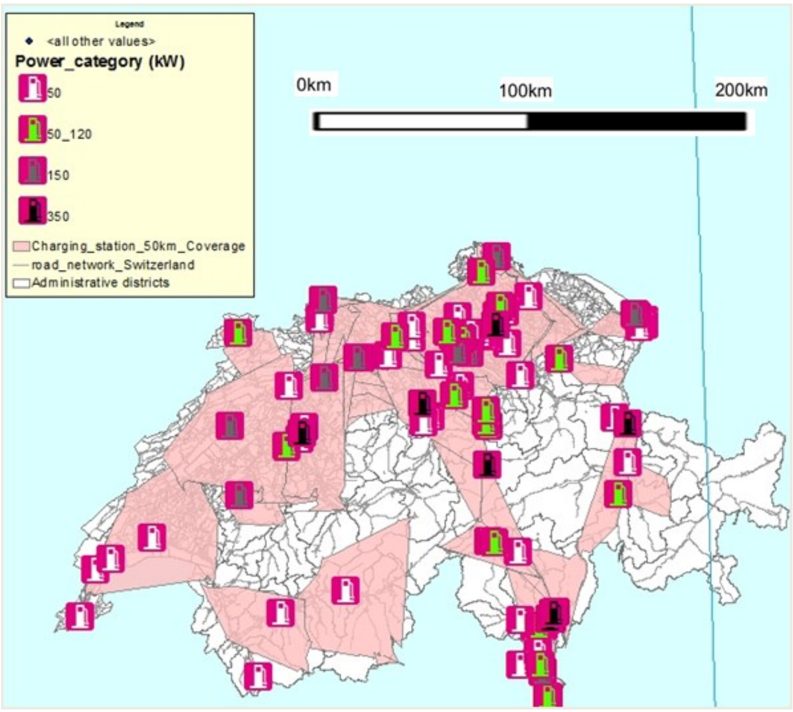


Figure 3. *Charging service area coverage of roadway fast-charging stations in Finland and Switzerland in early 2020 (Openchargemap 2020; Home.selasky 2020).*

The road networks may contain some errors due to some defects in nodes and links extraction from the Open Street Map web service. Other links such as Openchargemap (2020) and Home.selasky (2020) websites are used to build such datasets for both countries. The charging locations are filtered for the public fast charging stations with equal and bigger than 44 kW power.

Table 2. *Comparative charging service area coverage of on-road fast charging stations in Finland and Switzerland in early 2020 (Openchargemap 2020; Home.selasky 2020).*

	Finland	**Switzerland**
Total length of Network (km)	33,940.69	24,632.40
Total length of Network covered by 50 km coverage of charging stations (km)	13,912.79	17,439.80
Percentage of Network covered by 50 km coverage of charging stations	40.99%	70.80%
Total public charging stations	57	87
Total coverage area (overlaps included) km^2	12513.7	68176.4

Table 2 confirms the maps in Figure 3 by giving accurate numbers such as total length of network (including the motorway, primary, secondary, tertiary, and trunk roadway types) in km, total network length covered by charging service area in km, percentage of road network coverage, the total number of public charging station locations, and total coverage area in km^2. For instance, the percentage of road network covered by 50 km range charging service area of 40.99% and 70.80% for Finland and Switzerland, respectively, confirms such differences as is illustrated in the figure. This difference may be expected for the final simulation results of BEVPO models.

3.2.2 Travel data preparation

Travel survey data is briefly explained in the first step of BEVPO model. In this section, more details of travel survey data would be described. Regarding the instruction available in GitHub, a travel survey data must be defined by ".csv" format for each country.

The required fields are (1) "householdID" which refers to a unique ID for each household, (2) "personID" which refers to different person ID in a household, (3) "legID" which refers to the individual legs ID to complete a daily trip, (4) "distance" which refers to the distance of leg in km, (5) "legStartTime" and (6) "legEndTime" which refer to the start and end time of the leg in minutes after midnight, (7) "legStartAddress" and (8) "legEndAddress" which refer to the postal code of the leg's start (origin) to leg's end (destination) locations, (9) "legStartAddressAlt" and (10) "legEndAddressAlt" which refer to the name of the municipality of the given postal code, (11) "legStartAddressManual" and (12) "legEndAddressManual" which refer to other types of address if the Google map routing fails.

There are some other variables defined for travel purposes which may not be applicable for this thesis topic.

Accuracy of addressing in the travel survey plays a major role in the resulting accuracy of geo-routing assignment procedure in BEVPO model. As it is described in the previous paragraph, in BEVPO, the origin-destination (O-D) can be addressed primarily by postal codes, the municipality names, and for more accurate addressing, it can be extended by detailed addressing description. The postal code zones also are represented by PLZs. The PLZ refers to Postleitzahl which means “postal routing number” in Germany.

Travel surveys data used in this study is as a part of a continuous road freight surveys according to EU regulation for Finland and Switzerland (EU Regulation 2012). Travel survey data for Switzerland is achieved from BFS (BFS 2018) and for Finland is achieved from Statistics Finland in 2016 (Statistics Finland 2018). The sample survey data size in Finland is around 10,000 and the period of data collection is a 3-4 days per truck. While in Switzerland the sample survey data size is around 8,500 and the period of data collection is a week per truck. Two different data sheets including truck data and trip data are combined to make the final aggregated travel survey data. By considering individual grossing factor (to extend the whole year results) for each sample data, 84,544 and 18,110 trips are reported for Switzerland and Finland, respectively, in 2016.

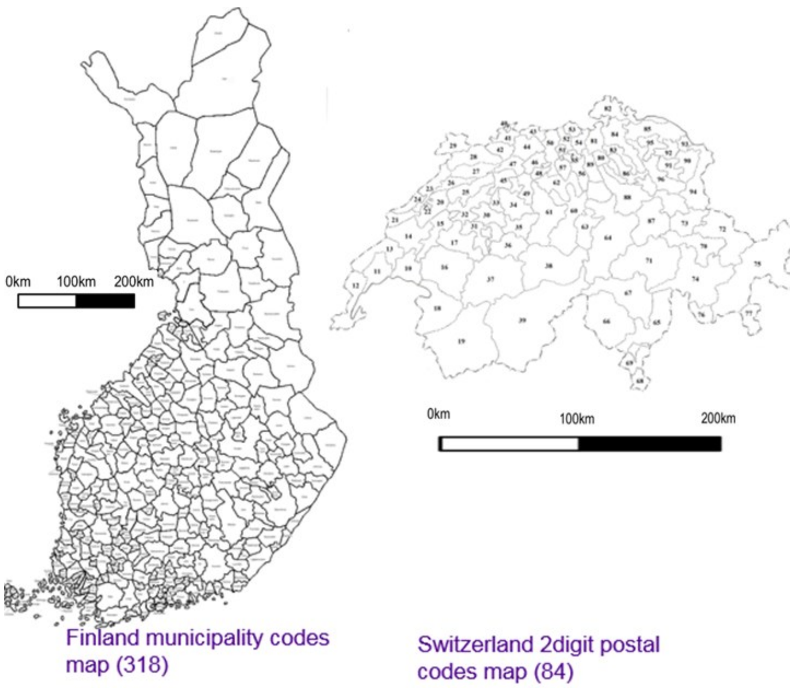


Figure 4. *Maps for Origin-Destination (O-D) visualization purposes in Finland and Switzerlan (Statistics Finland 2015; Opendata Swiss 2018).*

Switzerland' travel survey data are addressed by 4-digit postal code, whereas, Finland's travel survey data are addressed by municipality codes which is less accurate compare to the normal 5-digit postal codes in Finland. Switzerland' travel survey data is very accurate for using BEVPO model by addressing origin and destination via 4-digit postal codes which cover 4135 unique municipality codes (Opendata Swiss 2018). For visualization purpose, Switzerland's travel survey data can be summarized in 2-digit codes which includes 84 unique 2-digit postal codes. The proposal location for 2-digit codes visualization is calculated based on the closest 4-digit postal codes to the geometric centres of all 4-digit postal codes within a 2-digit postal code.

Finland's travel survey data is converted from 317 unique municipality codes to 317 unique 5-digit postal codes. There are approximately 3,117 unique 5-digit postal codes in Finland (Statistics Finland 2015). The proposal location for summarized 5-digit postal codes is calculated based on the closest 5-digit postal codes to the geometric centres of all 5-digit postal codes within a municipality code territory.

Figure 4 shows relevant maps for O-D data visualization purposes in Finland and Switzerland. Regarding the map of Finland, the addressing system in Finland is based on the illustrated municipality zones. While in Switzerland the addressing system is based on 4-digit postal code zones. Regarding the map of Switzerland, each of the 2-digit postal code zones approximately would be divided into 100 4-digit postal zones. As a result, the size of the zone address defined for travel survey data in Finland would be relatively larger than in Switzerland. Consequently, the accuracy of the addressing system in Switzerland would be more accurate than in Finland.

3.2.3 BET model specifications

Regarding the previous discussions about the battery capacity and range limits for long-haul freight transport by heavy-duty BETs in Chapter 2, the BET characteristics requirements for the BEVPO model simulation procedure can be predicted by the linear regression modelling. The idea will be discussed more in the following paragraphs.

Huismans (2018) has discussed different factors influencing on the energy consumption of the BEVs by explaining energy loss formulas in multilevel energy optimization (MEO) model which is a simulation tool to evaluate emission reduction potential for different studies such as in Van Zyl. Et al. (2017). The Willian Line powertrain model concept explains the relationship between energy loss internal, input, and output energy flows in MEO-model (Sorrentino et al. 2015). Huismans represented versatile energy-loss formulas applied in MEO-model in his study.

According to Huismans (2018), the power needed for the wheels consists of power for rolling resistance, air drag, inertia, and gradient. Except for the power for air drag, which was a function of the vehicle's size and shape, all other power functions have a linear relationship with the total weight of the vehicle. By assuming the air drag force is constant between different vehicle types, the energy consumption can be estimated through a linear regression prediction model for the higher payload capacities. However, considering the payload capacity instead of the gross vehicle weight for generating linear regression might cause standard errors which can be neglected in this thesis.

The energy-loss formula is a basic formula for energy loss calculation procedure which is combined with more detailed power loss factors such as power loss for transmission, braking, and heat in a new Willian line model concepts in the extended MEO-model. Such extended formula can provide accurate estimation for energy loss which is more than the accuracy needed for BEVPO model analysis. However, working with a simple linear energy loss formula, like equation (2), based on the driving distance in the BEVPO model is needed in this thesis. As a result, in order to make a rough estimation of energy consumption in kWh/km of the heavier payload's capacities, which are not feasible with the current technology, the linear regression model applies for some lighter available BET's technology.

In order to make the regression model, some of the available medium and heavy-duty BET models are collected from different online resources (Liimatainen et al. 2019; Huismans 2018; Mareev et al. 2018). The criterion for choosing such BET lists are: (1) the models are available for commercial purposes, and (2) they can reflect the current class 6 and 8 BETs' technology. Figure 5 illustrates the linear regression model for the energy consumption estimation for BETs of heavier payloads.

As it is discussed briefly in Section 3.2, BEV characteristics must be introduced to the BEVPO model for truck and trip simulation procedure. Regarding the above discussions, for using BEVPO model in road freight transport analysis, the travel survey data requires to be analysed in different truck classes with almost similar payload capacities.

However, specifying such truck classes can be challenging based on different factors such as gross vehicle weights (GVW), truck classes, lorry types (rigid, semitrailer, or trailer). For the sake of simulation procedure in BEVPO model and considering the payload capacity distributions in summary travel survey data in Finland and Switzerland, three truck classes are defined based on maximum payload capacities.

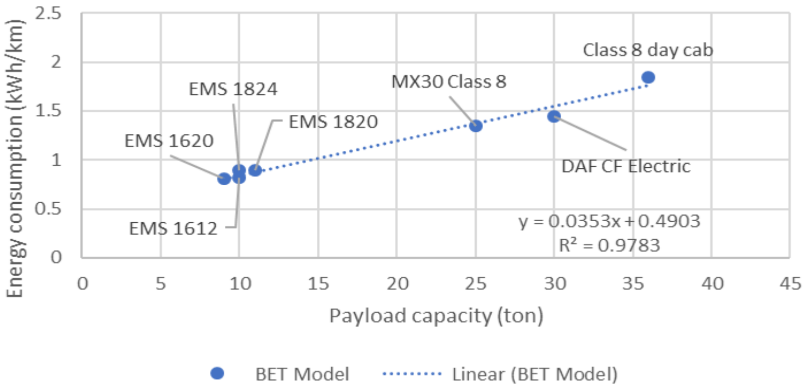


Figure 5. *The linear regression model for the energy consumption estimation of heavier BETs technology.*

The payload capacity classes are divided into the group 1 with payload capacities less and equal to 11 tons, group 2 with payload capacities between 11 to 30 tons, and finally group 3 with payload capacities bigger than 30 tons. The long-haul BETs model equivalents for the first two groups can be found based on the current technology, whereas, there is no technology currently available for the long-haul BETs in group 3 truck. Table 3 shows the data summary table for the three truck groups based on different payload capacities in Finland and Switzerland.

Table 3. *A comparative data summary table for the three truck groups based on different payload capacities in Finland and Switzerland.*

	Group 1: Trucks with payload up to 11 tons capacity	**Group 2: Trucks with payload 11-30 tons capacity**	**Group 3: Trucks with payload capacity greater than 30 tons**	**All truck types**
Finland				
Maximum payload capacity (ton)	11	30	58	58
Minimum payload capacity (ton)	0.3	11	30	0.3
Average payload capacity (ton)	5.3	20	42	30
Maximum payload (ton)	11	30	58	58
Minimum payload (ton)	0	0	0	0
Average payload (ton)	2.2	8.4	19.5	13.8
Annual average mileage (km)	37,870	50,726	75,347	55,983
Switzerland				
Maximum payload capacity (ton)	11	28	-	28
Minimum payload capacity (ton)	0.4	11	-	0.4
Average payload capacity (ton)	7.5	17.6	-	12.2
Maximum payload (ton)	11	28	-	28
Minimum payload (ton)	0	0	-	0
Average payload (ton)	3.5	7.4	-	5.4
Annual average mileage (km)	64,270	62,052	-	63,176

The table describes actual payload and payload capacities in three defined payload truck groups by using the minimum, maximum, and average measures according to travel survey data for Finland and Switzerland in 2016. As it is evident from the table, based on the road freight transport policy in Switzerland, there are no truck categories with more than 40 tons GVW. The 40 tons GVW limits is approximately equivalent for 30 tons payload capacity. While the road freight transport policies in Finland encourage the bigger size trucks and trailer trucks up to 76 tons for GVW which is equivalent for 58 tons payload capacity (Liimatainen et al. 2019). Regarding Figure 5 and Table 3, the BEVPO truck models for simulation purpose are finally defined based on the following assumptions.

For group 1 the truck models would be selected randomly from BET models of EMS 1612, EMS 1620, EMS 1820, and EMS 1824. For group 2, the truck model also would be selected randomly from BET models of MX30 Class 8, DAF CF Electric, and Class 8_day cab. However, for group 3, the imaginary BET models are defined based on energy consumption of 2.16 kWh/km with an average 43 payload capacity based on Figure 5. More details of the electric truck model definitions would be specified in the next section in different scenario packages.

3.2.4 Scenario packages

To analyse the impact of battery technology and charging facilities improvement in both countries, 5 different scenario packages are defined. The 4 of these scenario packages are defined based on the similarity of the 4 scenarios in the previous study with the same datasets by Liimatainen et al. (2019). Regarding scenario definitions in the previous study by Liimatainen et al. (2019), and considering each scenario package description in Table 4, scenario 1 in this study can be seen as the equivalent for the "current technology" scenario in previous one, whereas, scenario 3 to 5 by the assumption of gradual improvement for both battery capacity and fast-charging facilities can be seen as equivalent scenarios for "improved vehicles", "improved vehicles and charging", and "towards full electrification" scenarios in the previous study, respectively.

Scenario 2 is considered the electric road systems (ERSs) alternatives in some high demand freight routes for group 3 of trucks. According to the discussion in Chapter 2, group 3 of the payload capacity classification of trucks cannot be transported by BETs due to the technical limits in the current battery technology and fast charging facilities. Therefore, the ERSs like overhead line, rail, and inductive infrastructure can be considered as an alternative solution. More details about selecting alternative routes for ERSs alternatives are discussed in Chapter 2 and 5. The first two groups of payload capacity classification in scenario 1 can be simulated based on the assumptions of scenario 1 in Table 4.

Table 4. *The different Scenario packages attributes.*

	Description	*Battery technology on three different groups of payload capacities*	*Charging facility technology*
Scenario 1	BEVPO model based on the current battery technology capacity of BETs and first level improvement of the charging facilities in both countries.	Group 1 and group 2 BETs based on current technology for both countries. There is no EV truck simulation for current technology for both countries.	First level charging facility improvement: All current roadway charging facilities have been customised for providing services regarding the physical size of BETs such as parking dimensions. The charging power is divided to 50-50% between 50 and 120 kW for all charging activities.
Scenario 2	BEVPO model based on the current battery technology capacity of BETs and second level improvement of the charging facilities in both countries. The electric road scenario is also integrated to this scenario in Finland.	Group 1 and group 2 BETs based on current technology for both countries. There is no EV truck simulation for current technology of group 3 in both countries.	Second level charging facility improvement: All current roadway charging facilities have been customised for providing services regarding the physical size of BETs such as parking dimensions. The charging power is 150 kW for all charging activities.
Scenario 3	BEVPO model based on the first level improvement of battery technology capacity of BETs and third level improvement of the charging facilities in both countries.	First level battery technology improvement: Group 1 and group 2 BETs based on 50% growth rate of battery capacity and range of current technology for both countries. Group 3 EV truck simulation is considered based on the linear forecast model of current technology energy consumption.	Third level charging facility improvement: All current roadway charging facilities have been customised for providing services regarding the physical size of BETs such as parking dimensions. The charging power is 250 kW for all charging activities.
Scenario 4	BEVPO model based on the first level improvement of battery technology of BETs and Fourth level improvement of the charging facilities in both countries.	First level battery technology improvement: Group 1 and group 2 BETs based on 50% growth rate of battery capacity and range of current technology for both countries. Group 3 EV truck simulation is considered based on the linear forecast model of current technology energy consumption.	Fourth level charging facility improvement: All current roadway charging facilities have been customised for providing services regarding the physical size of BETs such as parking dimensions. The charging power is 450 kW for all charging activities.
Scenario 5	BEVPO model based on the second level improvement of battery technology of BETs and Fourth level improvement of the charging facilities in both countries.	Second level battery technology improvement: Group 1 and group 2 BETs based on 75% growth rate of battery capacity and range of current technology for both countries. Group 3 EV truck simulation is considered based on the 75% growth rate of calculated linear forecast model in Scenario 3 and 4.	Fourth level charging facility improvement: All current roadway charging facilities have been customised for providing services regarding the physical size of BETs such as parking dimensions. The charging power is 450 kW for all charging activities.

By considering different scenario packages which are represented in Table 4 and using different BET models defined in the previous section for each group of trucks, the group-specific BET models can be defined for different scenario packages in the BEVPO model. Table 5 illustrates the BET models' features for each group of payload capacity classification of trucks and different scenario packages.

Table 5. *BET settings for BEVPO model simulation procedures.*

	Scenario 1	*Scenario 2*	*Scenario 3*	*Scenario 4*	*Scenario 5*
Group 1 (payload capacity up to 11 tons)	EMS 1612: 10tons,125 km,120 kWh,0.816 kWh/km	EMS 1612: 10tons,125 km,120 kWh,0.816 kWh/km	EMS 1612 (+50%): 10tons,187.5 km,180 kWh,0.816 kWh/km	EMS 1612 (+50%): 10tons,187.5 km,180 kWh,0.816 kWh/km	EMS 1612 (+75%): 10tons,218.75 km,210 kWh,0.816 kWh/km
	EMS 1620: 9tons,210 km,200 kWh,0.81 kWh/km	EMS 1620: 9tons,210 km,200 kWh,0.81 kWh/km	EMS 1620 (+50%): 9tons,315 km,300 kWh,0.81 kWh/km	EMS 1620 (+50%): 9tons,315 km,300 kWh,0.81 kWh/km	EMS 1620 (+75%): 9tons,367.5 km,350 kWh,0.81 kWh/km
	EMS 1820: 11tons,190 km,200 kWh,0.89 kWh/km	EMS 1820: 11tons,190 km,200 kWh,0.89 kWh/km	EMS 1820 (+50%): 11tons,285 km,300 kWh,0.89 kWh/km	EMS 1820 (+50%): 11tons,285 km,300 kWh,0.89 kWh/km	EMS 1820 (+75%): 11tons,332.5 km,350 kWh,0.89 kWh/km
	EMS 1824: 10tons,230 km,240 kWh,0.89 kWh/km	EMS 1824: 10tons,230 km,240 kWh,0.89 kWh/km	EMS 1824 (+50%): 10tons,345 km,360 kWh,0.89 kWh/km	EMS 1824 (+50%): 10tons,345 km,360 kWh,0.89 kWh/km	EMS 1824 (+75%): 10tons,402.5 km,420 kWh,0.89 kWh/km
Group 2 (payload capacity 11-30 tons)	MX30 Class 8: 25tons,201 km,320 kWh,1.35 kWh/km	MX30 Class 8: 25tons,201 km,320 kWh,1.35 kWh/km	MX30 Class 8 (+50%): 25tons,301.5 km,480 kWh,1.35 kWh/km	MX30 Class 8 (+50%): 25tons,301.5 km,480 kWh,1.35 kWh/km	MX30 Class 8 (+75%): 25tons,351.75 km,560 kWh,1.35 kWh/km
	Class 8-day cab: 36tons,200 km,435 kWh,1.85 kWh/km	Class 8-day cab: 36tons,200 km,435 kWh,1.85 kWh/km	Class 8-day cab (+50%): 36tons,300 km,652.5 kWh,1.85 kWh/km	Class 8-day cab (+50%): 36tons,300 km,652.5 kWh,1.85 kWh/km	Class 8-day cab (+75%): 36tons,350 km,761.25 kWh,1.85 kWh/km
	DAF CF Electric: 30tons,100 km,170 kWh,1.45 kWh/km	DAF CF Electric: 30tons,100 km,170 kWh,1.45 kWh/km	DAF CF Electric (+50%): 30tons,150 km,255 kWh,1.45 kWh/km	DAF CF Electric (+50%): 30tons,150 km,255 kWh,1.45 kWh/km	DAF CF Electric (+75%): 30tons,175 km,297.5 kWh,1.45 kWh/km
Group 3 (payload capacity more than 30 tons)		New Group 3: 50tons,185 km,340 kWh,2.16 kWh/km (a)	New Group 3: 50tons,200 km,510 kWh,2.16 kWh/km	New Group 3: 50tons,200 km,510 kWh,2.16 kWh/km	New Group 3: 50tons,350 km,892.5 kWh,2.16 kWh/km

The table describes the different BET models' features. Accordingly, the BET models' features are the model name, payload capacity in ton, range in km, battery capacity in kWh, and energy consumption in kWh/km.

4. EMISSION AND COST EVALUATION

This chapter aims to provide a methodology for life cycle assessment (LCA) of $CO_{2,eq}$ emission as well as total cost of ownership (TCO) evaluation based on different scenario packages, defined in the previous Chapter, in Finland and Switzerland. The LCA will be separately discussed in two following sections of well-to-wheel (WTW) emission and additional to WTW emission categories. TCO evaluation also will be discussed in the last section. Limited academic resources were found discussing these topics for the BET related technologies; therefore, many assumptions and uncertainties includes in both methodologies.

4.1 Well-to-Wheel (WTW) emission

Well-to-wheel (WTW) emission analysis is an important element of LCA methodology for the evaluation of total greenhouse gas (GHG) produced by different types of vehicles. In brief, LCA includes different phases such as vehicle manufacturing, maintenance, use phase and the end-of-life (EOL) phase. The use phase will be discussed as WTW in this section which considers emissions related to energy consumption, and production for a vehicle. The other emission sources than WTW in LCA will be discussed as additional emission to WTW in the next section.

WTW is divided into well-to-tank (WTT) and tank-to-wheel (TTW) emission types. WTT is considered as emission generated in the supply chain process for different fuel types which can be extended by different activities such as production and conditioning at source, transformation at source, transportation to market, transformation near market, and conditioning and distribution. TTW is also considered as the part of emission which comes directly from the vehicles (Hass et al. 2014; Eriksson and Ahlgren 2013).

Regarding the scenario packages defined in Chapter 3, two vehicle-type of conventional truck (CT) and battery electric truck (BET) will be evaluated in each scenario. Accordingly, WTW elements are defined in the following paragraphs for the given truck types.

4.1.1 WTW emission for Conventional Trucks (CTs)

The fuel type in CTs is assumed to be the diesel. Therefore, both WTW emission parts of WTT and TTW for diesel fuel emission will be calculated based on the following assumptions. According to Eriksson and Ahlgren (2013), regarding different factors impacting on supply chain and production of diesel fuel in Europe, the WTT vary for a range between 0.0014 to 0.0047 $CO_{2,eq}$ kg/kWh. Since the available resources barely stated the WTT measure in Finland and Switzerland; therefore, by considering a well-running supply chain for diesel fuel in both countries, the WTT is assumed to be 4 $CO_{2,eq}$ g/kWh.

For the TTW emission calculation and fuel consumption by CTs, all assumptions and methodology are based on the previous study by Liimatainen et al. (2019). The assumptions are summarized as the following steps. Firstly, the total weight of trucks (GVW) is based on the available travel survey datasets in both countries. Secondly, diesel consumption in each trip is calculated based on the total weight of trucks by using the formula illustrated in the following equation developed by Liimatainen and Pöllänen (2010):

$$FC = 5.7767 \times W^{0.6672} \quad (3)$$

Where FC represents the diesel consumption per 100 km and W is the total weight of the vehicle in tons. The formula is based on average diesel consumption of emission class Euro 0 trucks in urban roads. The other emission class would be calculated by following coefficients of 0.931, 0.924, 0.948, 0.899, and 0.909 for Euro 1, Euro 2, Euro 3, Euro 4, Euro 5/6 trucks, respectively. Third, the total CO_2 emissions of the trip would be calculated by multiplying the total diesel consumption in litres by 2.66.

Fourth, the total diesel energy consumption in kWh is calculated by multiplying the total diesel fuel consumption in litres by 9.794. The electric energy consumption is calculated by dividing the diesel energy consumption by 2.5. The ratio is based on research conducted by Mareev et al. (2018) which can be varied between 2.4 and 2.7 based on average and heavy routes.

4.1.2 WTW emission for Battery Electric Trucks (BETs)

According to multiple resources (Hass et al. 2014; Eriksson and Ahlgren 2013), WTW emission for BEV only includes WTT emissions and the amount of TTW emissions for these types of vehicle is almost equal to zero. The WTT emission varies based on the source of mixed electricity grid generation. The greener mixed grid electricity sources, the closer $CO_{2,eq}$ kg/kWh emission to zero for WTT in BEVs. The mixed grid electricity generation emissions vary in different countries with different sources of energy consumption for electricity generation.

According to the report of the Carbonfootprint (2019) website about the country-specific electric greenhouse gas emission factors, Finland and Switzerland are in the top list of countries using the greenest energy sources. For Finland, the more accurate and real-time emission factors are available via the Fingrid (2020) website. According to the given resources, the average emission of 0.085 and 0.014 $CO_{2,,eq}$ kg/kWh is assumed for Finland and Switzerland, respectively, based on the current infrastructures.

The uncertainty level for the given assumption can be estimated by the sensitivity analysis of WTW or LCA emission based on the variation of WTT supply energy source scenarios for the grid electricity generation. Accordingly, the sensitivity analysis will be conducted in Chapter 5 with the range of +/- 50% according to the given average emission assumption in both countries for BET scenarios in this section.

4.2 Additional $CO_{2,eq}$ emission to WTW

The methodology and relevant assumptions for calculating additional to WTW emission in LCA of CT and BET scenario packages are mainly adopted from Huismans (2018). However, many other assumptions are extended for each scenario packages defined in Chapter 3 based on the other available resources. The additional WTW emission in LCA of CTs and BETs consist of (1) production emission, (2) maintenance and repair emission, and (3) EOL phases. In this thesis, the phase 1 and 2 would be discussed in the following paragraphs. But, due to the lack of information about the EOL of the different class of CTs and BETs, the third phase is omitted in this thesis.

4.2.1 Production phase

Huismans (2018) divided the total CO_2 equivalent ($CO_{2,eq}$) of production phase into three categories of trucks based on their total weight such as 16, 28, and 40 tons. The given classification can provide a rough estimate for the relevant truck payload classification defined in Chapters 3. The production emission will be discussed separately for two different types of vehicles in the following section.

According to calculations provided by Wernet et al. (2016; cited by Huismans 2018) for different size of lorries, the production emission for CTs can be assumed as 22,215, 33,049, and 47,400 $CO_{2,eq}$ in kg with the payload capacity classifications of up to 11 tons, 11 to 30 tons, and more than 30 tons, respectively. The production emission in group 3 of CTs is based on some expert evaluation and smaller size of lorries. It might be less accurate compared to the other truck classes, but there is no available information for such heavier vehicle production emission estimation.

According to Huismans (2018), the production emission for BETs consists of (1) the production emissions of CTs based on previous paragraphs, (2) emission related to the charger production, and (3) emission related to battery production. For the first part, the relevant figures simply are copied from the CT types. For the second and third parts, the following equation would be applied based on a combination of different resources (FEV report 2018; Peters and Weil 2018; cited by Huismans 2018):

$$CO_{2eq,prod} = CO_{2eq,CT} + 96 + \frac{266.6}{0.8} \times Battery\ capacity(kWh) \quad (4)$$

Where, the $CO_{2eq,CT}$ is $CO_{2,eq}$ emission for the CTs in kg and the battery capacity is the total battery capacity during the whole lifetime of the BETs. In this thesis, the battery and vehicle lifetimes are assumed 4 and 8 years, respectively, for all BET classes in the scenario packages in Chapter 3.

4.2.2 Maintenance and repair phase

Huismans (2018) divided the total $CO_{2,eq}$ of maintenance and repair phase into three categories of trucks based on their total weight such as 16, 28, and 40 tons. According to the calculations provided by Wernet et al. (2016; cited by Huismans 2018) for different size of lorries, the maintenance and repair emission for CTs can be assumed as 11,901, 11,901, and 19,114 $CO_{2,eq}$ in kg with payload capacities up to 11 tons, 11 to 30 tons, and more than 30 tons, respectively. The given numbers are rough estimations based on the smaller size of CTs. Due to the lack of information about the maintenance and repair emission in group 1 of the CTs, the relevant figures in group 1 is assumed to be equal to group 2.

For BETs, the maintenance and repair emission were reported to be less than 0.3 to 0.85 of the same figures by CTs according to multiple references (Onat et al. 2015; Propfe et al. 2012; cited by Huismans 2018). Therefore, considering 50% of the relevant figures in the CTs can be properly assumed for the maintenance and repair emission of BETs.

4.2.3 Summary tables for additional $CO_{2,eq}$ emission to WTW

Regarding the given assumption in Section 4.2.1 and 4.2.2, the additional emission to WTW in LCA based on different CT and BET classes are summarized in Table 6. The table illustrates the WTW emission figures in $CO_{2,eq}$ kg per vehicle types.

To perform an average annual analysis for LCA, the annual factors of additional $CO_{2,eq}$ emission are calculated based on the following assumptions: (1) 10-years lifetime for CTs, (2) two batteries with 190 kWh capacity for scenario 1 and 2, two batteries with 285 kWh capacity in scenario 3 and 4, and two batteries with 330 kWh capacity for scenario 5 would be used in 8 years lifetime for BETs up to 11 tons payload capacities, (3) two batteries with 340 kWh capacity for scenario 1 and 2, two batteries with 510 kWh capacity in scenario 3 and 4, and two batteries with 600 kWh capacity for scenario 5 would be used in 8 years lifetime for BETs with 11-30 tons payload capacities, and (4) two batteries with 340 kWh capacity for scenario 2, two batteries with 510 kWh capacity in scenario 3 and 4, and two batteries with 820 kWh capacity for scenario 5 would be used in 8 years lifetime for BETs more than 30 tons payload capacities.

Table 6. *Data summary assumptions for the additional emission to WTW in different truck payload classifications in $CO_{2,eq}$ kg (Adopted and modified from Huismans 2018)*

	Conventional Trucks			Battery Electric Trucks		
Payload capacity in tons	Production	Maintenance and repair	Additional to WTW emission	Production	Maintenance and repair	Additional to WTW emission
Up to 11	22,215	11,901	34,116	96+22,215+266.6*(kWh capacity of battery)/80%	5,951	28,262+266.6*(kWh capacity of battery)/80%
11-30	33,049	11,901	44,950	96+33,049+266.6*(kWh capacity of battery)/80%	5,951	39,096+266.6*(kWh capacity of battery)/80%
More than 30	47,400	19,114	66,514	96+47,400+266.6*(kWh capacity of battery)/80%	9,557	57,053+266.6*(kWh capacity of battery)/80%

By developing Table 6 contents to the different scenario packages defined in Chapter 3, the lifelong additional $CO_{2,eq}$ emission table can be calculated. Table 7 shows the annual additional $CO_{2,eq}$ emission for group 1 to 3 payload classification of CTs and BETs.

Table 7. *Annual additional $CO_{2,eq}$ emission to WTW for different scenario packages per truck in $CO_{2,eq}$ kg.*

Different Scenarios	Conventional Trucks		Battery Electric Trucks	
Payload capacity up to 11 tons	Lifelong assessment	Annual additional $CO_{2,eq}$	Lifelong assessment	Annual additional $CO_{2,eq}$
Scenario 1	34,116	3,412	154,897	19,362
Scenario 2	34,116	3,412	154,897	19,362
Scenario 3	34,116	3,412	218,215	27,277
Scenario 4	34,116	3,412	218,215	27,277
Scenario 5	34,116	3,412	248,207	31,026
Payload capacity 11 to 30 tons				
Scenario 1	44,950	4,495	265,706	33,213
Scenario 2	44,950	4,495	265,706	33,213
Scenario 3	44,950	4,495	379,011	47,376
Scenario 4	44,950	4,495	379,011	47,376
Scenario 5	44,950	4,495	435,664	54,458
Payload capacity above 30 tons				
Scenario 1	66,516	6,652	-	-
Scenario 2	66,516	6,652	283,663	35,458
Scenario 3	66,516	6,652	396,968	49,621
Scenario 4	66,516	6,652	396,968	49,621
Scenario 5	66,516	6,652	603,583	75,448

Table 7 describes how the annual additional $CO_{2,eq}$ would change by truck type and class in different scenario packages. It also reflects some important facts which are summarized as (1) the heavier truck classes produce the more emissions, (2) the additional $CO_{2,eq}$ emissions for BETs are far bigger than for CTs with the same scenario and truck class, and (3) the difference between additional $CO_{2,eq}$ emissions of BETs and CTs increases when the size of the battery is increased by scenario packages. The fact that the battery size plays a major role in the LCA of BEV, according to multiple resources (Kawamoto et al. 2019; Onat et al. 2015; Peters and Weil 2018), is reflected in the table contents.

4.3 Total Cost of Ownership (TCO)

According to Van Velzen (2016), total cost of ownership (TCO) in the EVs can be influenced by different factors such as the vehicle or charging specs, customer specs, number of EVs sold globally, and production cost of EVs. However, TCO can be simply defined in generic terms including two main costs of one-time cost (OTC) and recurring cost (RC). The OTC is considered as the fixed lifelong cost of the vehicle, but the RC should be calculated as the net present value (NPV) of the potential future recurring costs. According to multiple resources (Van Velzen 2016; Sen et al. 2017; Zhou et al. 2017; cited in Huismans 2018), TCO for different type and size of vehicles can be calculated from the following equation:

$$TCO = OTC + \sum_{n=1}^{N} RC \times \frac{1}{(1+i)^n} \quad (5)$$

The OTC and RC formula can be specified for EVs as the following equations:

$$OTC = p_v + \frac{€_{kWh}}{kWh} \times C_{battery} + p_{infra} \times n_{chargers} \quad (6)$$

$$RC = \frac{€_{maint}}{km} \times km_y + \frac{€_{charging}}{km} \times km_y + \frac{€_{fuel}}{kWh} \times u_{meo} \times km_y \quad (7)$$

Where, p_v is the price of vehicle technology, $\frac{€_{kWh}}{kWh} \times C_{battery}$ is the cost of battery based on battery capacity, $p_{infra} \times n_{chargers}$ is the price of a charging station multiply by the number of chargers, $\frac{€_{maint}}{km} \times km_y$ is the cost of maintenance of the vehicle based on the distance driven per year, $\frac{€_{charging}}{km} \times km_y$ is the fast-charging price based on the distance driven per year , and $\frac{€_{fuel}}{kWh} \times u_{meo} \times km_y$ is the cost of fuels based on the distance driven per year. Accordingly, the above 6 crucial TCO elements would be discussed in the following paragraphs. Regarding the high level of uncertainty involved in the estimation of the given TCO elements, all the costs would be specified for the low, average, and high cost scenarios.

4.3.1 Vehicle costs

The vehicle costs are OTCs for CTs and BETs. They only include the vehicle technology and powertrain (excluding the cost of the battery), which was discussed by Van Velzen (2016) to be the same based on the previous studies (Sen et al. 2017; Zhou et al. 2017; Zhao et al. 2016; Verbeek et al. 2018). The following table illustrates the specified prices for different payload truck classes per vehicle.

Table 8. *Vehicle costs for different payload truck classes in euros (Sen et al. 2017; Zhou et al. 2017; Zhao et al. 2016; Verbeek et al. 2018)*

€ per Vehicle	Low	Baseline	High
Payload capacity up to 11 tons	70,385	78,205	86,026
Payload capacity 11 to 30 tons	100,000	110,000	120,000
Payload capacity above 30 tons	120,000	132,000	144,000

The table shows the prices with assumption of +/- 10% change of baseline for high and low-price scenarios for both of CTs and BETs. Accordingly, the truck costs vary from 70,385 to 144,000 € based on different truck classes.

4.3.2 Battery technology costs

The Cost of Battery technology is an OTC. It plays a major role in the TCO analysis of BEVs. Regarding future development in battery technology manufacturing, it is expected that the cost of battery technology will be reduced in the next decades (Van Velzen 2016).

The future improvement also is expected in the performance of batter by increasing the battery cycles from 3,000 to 6,000 in two decades (Tesla Motors 2016). The price of the battery varied from 266 to 551 €/kWh in 2015 and it is expected to reduce for the following years (Van Velzen 2016).

According to Bloomberg New Energy Finance (BNEF), the average battery technology price market in 2019 was 157 €/kWh (BNEF 2019). Therefore, the baseline cost of the battery in this thesis would be assumed 160 €/kWh with +/- 30% variation for the high and low-price scenarios. In this thesis, the likely continuing and expected decrease in battery prices for the future is not considered. Table 9 shows the cost of battery technology for each BET based on different scenario packages defined in Section 3.2.4 in Chapter 3.

Table 9. *Cost of battery technology per BET in different scenario packages in € (BNEF 2019).*

€ per Vehicle		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Payload capacity up to 11 tons	Low	41,707	41,707	62,561	62,561	72,439
	Baseline	54,219	54,219	81,329	81,329	94,170
	High	70,485	70,485	105,727	105,727	122,421
Payload capacity 11- 30 tons	Low	74,634	74,634	111,951	111,951	130,609
	Baseline	97,024	97,024	145,536	145,536	169,792
	High	126,131	126,131	189,196	189,196	220,729
Payload capacity above 30 tons	Low	-	74,634	111,951	111,951	179,999
	Baseline	-	97,024	145,536	145,536	233,999
	High	-	126,131	189,196	189,196	304,198

The table shows how the price increases due to the increase in the battery size in different scenario packages as well as payload capacity classes. The least cost of battery belongs to BETs with payload capacity up to 11 tons in scenario 1, while, the highest cost of battery belongs to BETs with payload capacity above 30 tons in scenario 5.

4.3.3 Charging and infrastructure costs

The charging costs are the RC. However, the charging infrastructure costs are OTC. They were discussed in the multiple studies (Schroeder and Traber 2012; Verbeek et al. 2018; Mareev et al. 2018). Huismans (2018) provided fast charging cost infrastructures based on different routes. The costs varied from 0.08 to 0.19 €/kWh regarding the availability of fast charging facilities. The costs were calculated based on the lowest (50%) to the highest rate (91%) of using fast charging during the day.

Regarding the scenario packages defined in Section 3.2.4 in Chapter 3, the share of fast-charging facilities for the first two scenarios is lower compared to the others. Therefore, by rough estimations for the scenario 1, the cost of charging infrastructures is assumed 0.1 +/-0.01 (10%) €/kWh, whereas, for other scenarios with full fast charging of equal and bigger than 150 kWh power, the cost of charging infrastructure is assumed 0.2 +/-0.02 (10%) €/kWh.

4.3.4 Maintenance costs

The maintenance costs are the RC. According to multiple studies (Sen et al. 2017; Zhou et al. 2017; Zhao et al. 2016; Verbeek et al. 2018; cited by Huismans 2018), the cost of maintenance is customised based on the different truck classes. Expert views were implemented by Huismans (2018) to estimate the cost of maintenance in €/km. Table 10 represents the customised cost of maintenance for different payload class of CTs and BETs by +/- 10% variation.

***Table 10.** Maintenance Costs of different truck types in €/km (Huismans 2018)*

€ per km	Conventional Trucks			Battery Electric Trucks		
	Low	Baseline	High	Low	Baseline	High
Payload capacity up to 11 tons	0.074	0.082	0.090	0.057	0.064	0.070
Payload capacity 11- 30 tons	0.139	0.155	0.170	0.053	0.059	0.065
Payload capacity above 30 tons	0.111	0.123	0.135	0.098	0.109	0.120

The table shows that the maintenance costs for the CTs are relatively higher than the BETs. Accordingly, the maintenance costs vary from 0.053 to 0.17 €/km based on different truck classes.

4.3.5 Fuel and electricity prices

The fuel price in CTs and electricity price in BETs are also the RC. The price of diesel fuel is adopted from the Globalpetrolprices (2020) website for both countries. The price of fuel varies during different timeframes and is affected by different national and global factors. The average prices are assumed to be 1.3 and 1.42 €/l of diesel fuel by considering +/- 10% variation for Finland and Switzerland, respectively.

Similarly, the average cost of electricity is adopted from the Globalpetrolprices (2020) website for business purposes. The average prices are assumed to be 0.12 and 0.15 €/kWh by considering +/- 10% variation for Finland and Switzerland, respectively.

4.3.6 Discount ratio

The discount ratio will be used for calculating the relevant NPV of RCs. According to Van Velzen (2016; cited by Huismans 2018), the discount rates in the literature can be varied from 4% to 30% for different vehicle types.

In this thesis, the discount rate is assumed a small ratio equal to 5%. In addition, the uncertainty range for this value would be assumed to be +/- 50% for both countries.

4.3.7 TCO analysis and sensitivity analysis

The results of TCO analysis in different scenario packages will be evaluated in each country based on the BEVPO model analysis. Accordingly, the comparative TCO analysis can reflect the difference between TCO in CTs and BEVs vehicle types in both countries.

Moreover, the sensitivity analysis can be applied for TCO based on different parameters in two countries such as the fuel cost, one-time costs, discount rate, maintenance cost, and fast charging. Accordingly, the relevant results will be represented in Section 5.4 in Chapter 5.

4.4 Action costs and abatement costs analysis

According to Berger (2016), the abatement costs for GHG reduction potential can be a cost-efficiency measurement tool to compare different alternative decarbonizing solutions in the transport sector. Berger (2016) defined the $CO_{2,eq}$ abatement costs by the differentiation costs in the potential WTW reduction unit as €/ton $CO_{2,eq}$. Berger 2016 represented that BEV technology has the third least $CO_{2,eq}$ abatement costs after biofuel and full hybrid engine alternatives. The $CO_{2,eq}$ abatement costs measure can be used in the cost-efficiency analysis not only for different vehicle technology alternatives but also for different scenario alternatives of specific vehicle technology.

However, the $CO_{2,eq}$ abatement costs definition by Berger (2016) does not consider the impact of additional $CO_{2,eq}$. Thus, for the cost-efficiency analysis between different scenario packages in this thesis, the LCA measure will be used for the $CO_{2,eq}$ abatement costs calculation instead of the WTW emission. In order to distinguish the cost-efficiency measures, the new version of $CO_{2,eq}$ abatement costs definition will be named as "action costs for $CO_{2,eq}$ LCA reduction". Moreover, the differentiation costs and emission reduction potential will be calculated based on the 10 years for all scenario packages to synchronize the annual operational costs. Further discussion about how to implement both the cost-efficiency measures will continue in Chapter 5.

5. RESULTS AND ANALYSIS

This chapter aims to represent and discuss the important results from different stages of data analysis. Accordingly, in Section 5.1, the data summary analysis will be represented by different data visualization tools. In Section 5.2, the simulation results of the BEVPO model analysis will be represented for different scenario packages of BETs. Furthermore, different alternative solutions such as the extended range technology and ERSs will be discussed in this section. In Section 5.3 and Section 5.4, $CO_{2,eq}$ LCA and TCO of different scenario packages of BETs and CTs will be analysed. Finally, in Section 5.5, the action costs for the $CO_{2,eq}$ LCA reduction potential will be represented and discussed. Additionally, in this section, the best alternative scenario packages will be represented based on factors such as the total $CO_{2,eq}$ LCA reduction potential and the action costs for the $CO_{2,eq}$ LCA reduction potential. Regarding the extended information in Section 3.2.2 about the data preparation, all the measures in this chapter will be represented by extending to the whole year data (by using gross factors of travel survey data) in 2016.

5.1 Data summary results

In this section, first, the summary of the travel survey data in 2016 in Finland and Switzerland are analysed based on important parameters such as freight type categories, European emission standards, tonnage, mileage, ton-km (tkm), $CO_{2,eq}$ emission, and the number of trips in the freight transports. Second, extensive spatial data analysis is applied to the given travel survey data by using R programming in both countries. As a result, desire lines and trip generation/attraction maps are produced for a comparative analysis in road freight transport in Finland and Switzerland in 2016.

5.1.1 Summary road freight travel survey data analysis

Based on the methodology described in previous chapters, the following note must be noticed in the results. First, regarding the detailed discussion in Chapter 3, the payload classification is based on three payload categories of up to 11 tons, between 11 to 30 tons, and above 30 tons. Second, the fuel consumption and relevant $CO_{2,eq}$ emission are calculated from the given equations in Section 4.1. Third, all the measures represented in this chapter such as trip number, mileage, tonnage, and tkm are scaled up based on the different gross factors mentioned in the data preparation procedure in Section 3.2.2.

Accordingly, Table 11 provides a comparative summary analysis of road freight transport by medium and heavy-duty trucks based on some import factors in Finland and Switzerland in 2016.

Table 11. *Comparative summary of road freight transport with medium and heavy-duty trucks in Finland and Switzerland in 2016.*

	Finland	Switzerland	Finland / Switzerland
Trip Numbers in million	25.87	48.48	0.53
Mileage in million km	1,875.82	1,666.12	1.13
Tonnage in million ton	274.54	273.78	1.00
Ton-km in million tkm	24,585.52	10,107.79	2.43
Diesel fuel in million litres	926.90	617.36	1.50
Direct $CO_{2,eq}$ emission (TTW) in k tons	2,465.56	1,642.17	1.50

Figure 6 also illustrates a relevant comparative road freight analysis based on the different payload capacity classification. The table also illustrates that the trip numbers in Switzerland are almost twice that in Finland. In other factors, Finland has bigger values compare to Switzerland. Interestingly, the tonnage and mileage figures are almost the same in both countries. Moreover, the fuel and the relevant direct $CO_{2,eq}$ (TTW) emission in Finland are 1.5 times that in Switzerland. The tkm value comprises the biggest variation amongst the other figures in this analysis, where the tkm in Finland is 2.5 times that in Switzerland.

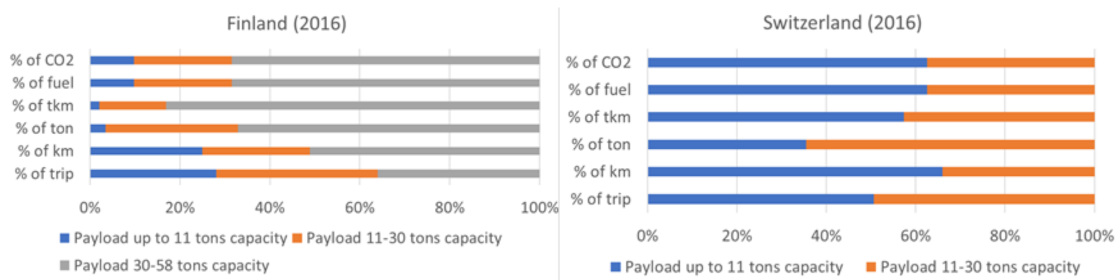


Figure 6. *Comparative travel survey data analysis of road freight transport with medium and heavy-duty trucks in Finland and Switzerland based on payload classifications in 2016.*

The figure shows the share of direct $CO_{2,eq}$ emission (TTW), fuel consumption, tkm, tonnage, mileage, and trip number measures for different payload capacity classification of road freight transports in Finland and Switzerland in 2016. Accordingly, on the one hand, Switzerland's road freight transport heavily relies on smaller cargo and truck sizes. This is because, according to Liimatainen et al. (2019), the freight policy in Switzerland limits the truck movement with GVW heavier than 40 tons (maximum payload capacity of 30 tons). Regarding the figure, first, the trip numbers are equally distributed between two payload capacity classification groups. Second, the smaller cargos are utilized for the shorter mileage distribution, whereas, the bigger cargos are utilized for the heavier load distribution.

On the other hand, based on the compromising freight management strategy and policy in Finland, the bigger size of freight transport, up to 76 tons for GVW which can be equivalent to 58 tons payload capacity, is allowed in the road networks. Regarding the figure, the number of freight trips is distributed equally between three payload capacity classification. But, the mileage, tonnage, and tkm measures show that: (1) the shorter trip distances the smaller cargos and (2) the majority of freight road trips are carried by the long-haul trucks with the payload capacities heavier than 30 tons. The difference between the different road freight distribution systems and policy strategies may rely on the road network facilities and infrastructures. Figure 7 provides more details about the share of different fuel emission standards in both countries.

The figure shows the distribution of diesel consumption based on the fuel emission standards categories. The diesel consumption values are illustrated by the line graph with the vertical scale units of the right axis in million tkm. The left axis represents the tkm share of different payload capacity classes for different emission standards illustrated by the column charts. The line graphs in the figure illustrate that the major share of diesel fuel consumption is based on Euro V and VI standard. This means that there is less potential of direct emission reduction through upgrading internal combustion engine vehicle (ICEV) from the old technology to the latest and greenest one. However, this is a very generic conclusion and more details in the emission standard and engine optimization technology are out of this thesis’s scope.

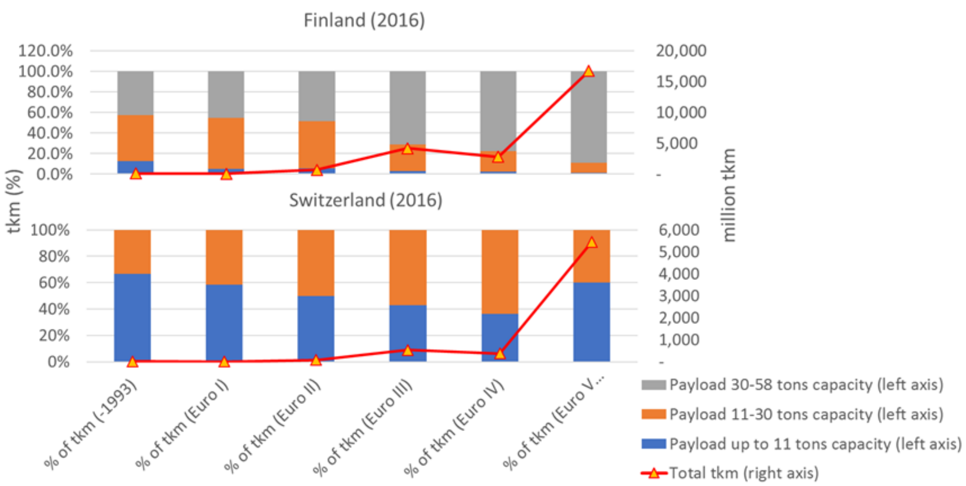


Figure 7. *Comparative fuel consumption shares in Finland and Switzerland based on European emission standards and payload capacity distribution.*

Figure 8 represents a comparative analysis of different load type based on NST2007 commodity groups defined in the European Commission (Eurostat 2018). The right axis illustrates the tkm values for different NST2007 commodity group which is illustrated by line graphs. Except for some small changes in the line graphs, the trend of NST2007 commodity share in the two countries is similar. The left axis illustrates the tkm share of different payload capacity classes for different NST2007 commodity groups illustrated by the column charts. The column charts follow the general theme of tkm share represented in Figure 8 with some fluctuation in different NST2007 commodity groups for both countries.

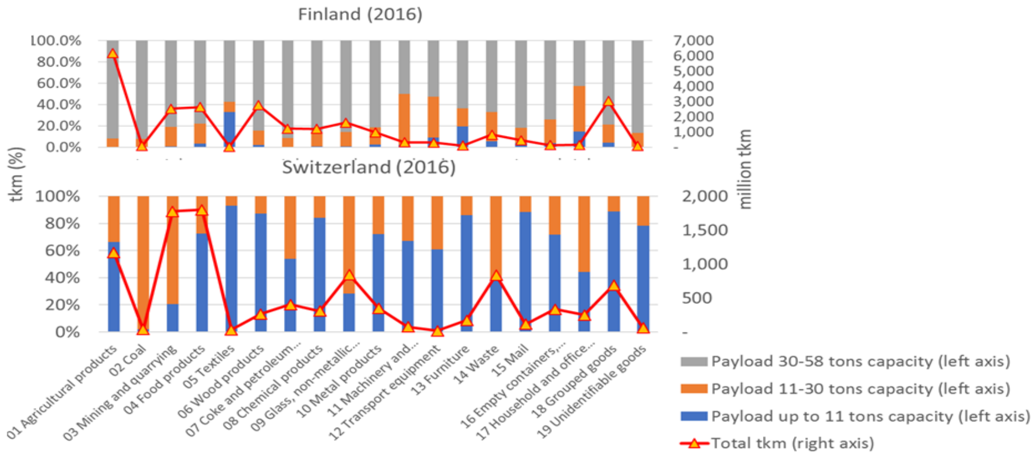


Figure 8. *Comparative tkm shares of different commodity group types of NST2007 in Finland and Switzerland based on payload capacity distribution.*

The figure reflects that, on the one hand, in Finland, the commodity group of (01) agriculture products, in which soil material transport is the most important commodity, has the first largest share, and (18) grouped goods, (06) wood products, (04) food products, and (03) mining and quarrying have the second-largest shares. On the other hand, in Switzerland (04) food products, (03) mining and quarrying take the first places as the top largest share in NST2007 commodity, and the second place belongs to (01) agriculture products.

5.1.2 Geospatial analysis of the travel survey data

Different visualization maps and techniques such as origin-destination (OD) data analysis, desire lines, trip generation/attraction, and rout assignment maps can be applied for transport planning. There is a wide range of transport planning software such as EMME4, and transCAD which can facilitate such transport planning tasks. Unfortunately, most of them are not freely accessible. Limited numbers of open-source packages such as stplanr in R can be accessible and accountable as a more transparent and democratic alternative for such expensive software.

Lovelace and Ellison (2018) discussed different applications of the stplanr package by providing specific examples of big datasets for doing different transport planning tasks.

The following maps and visualizations are produced by using the different R packages such as stplanr to provide more detailed geospatial analysis of the travel survey data in both countries.

Figures 9 to 11 show a comparative geospatial visualization of the travel survey data for the different payload capacity classifications in Finland and Switzerland. Regarding the inside zone trip generation/attraction bar charts and the desire lines illustrated in the maps, the fact that the heavier cargos in Finland are implemented for the longer haul mileage trips has been confirmed. However, such a conclusion cannot be inferred only based on the given maps.

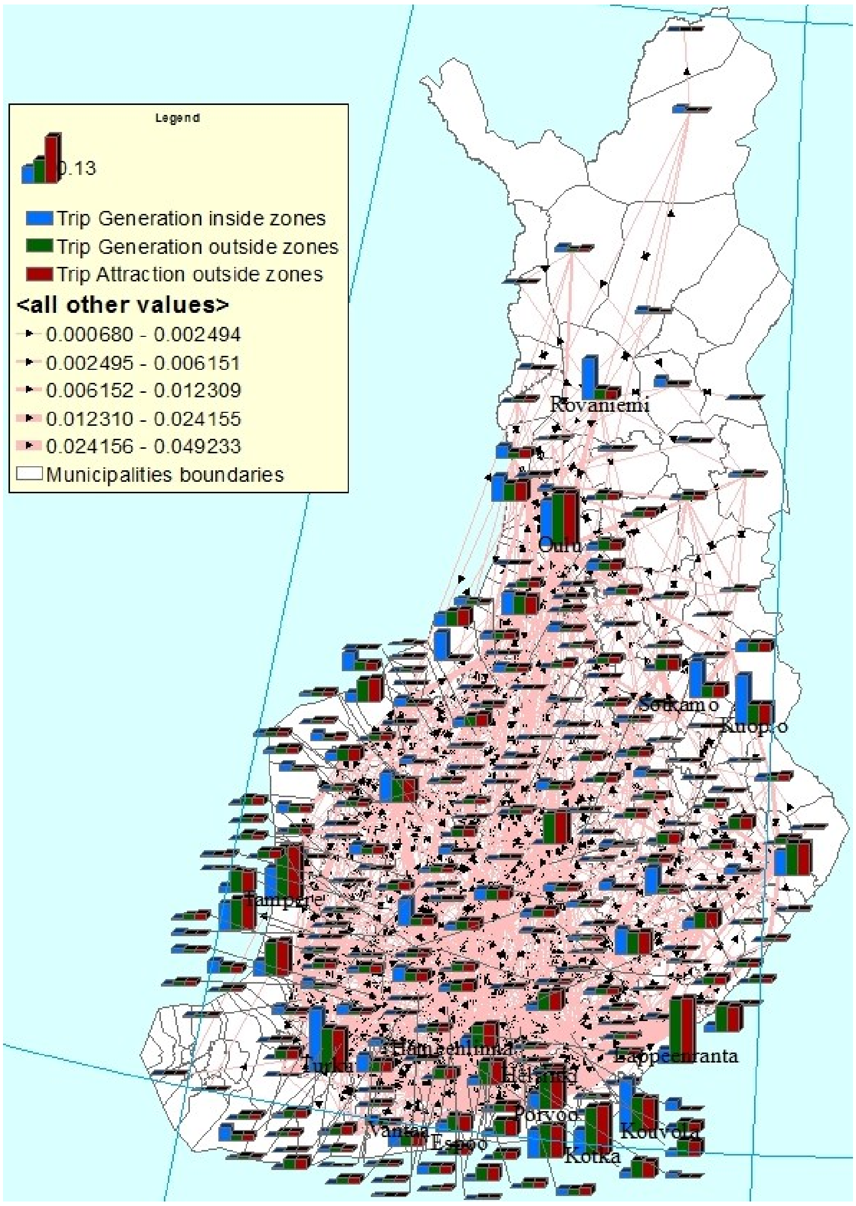


Figure 9. *Map of travel survey data for above 30 tons payload capacity based on trip generation and attraction in million trips.*

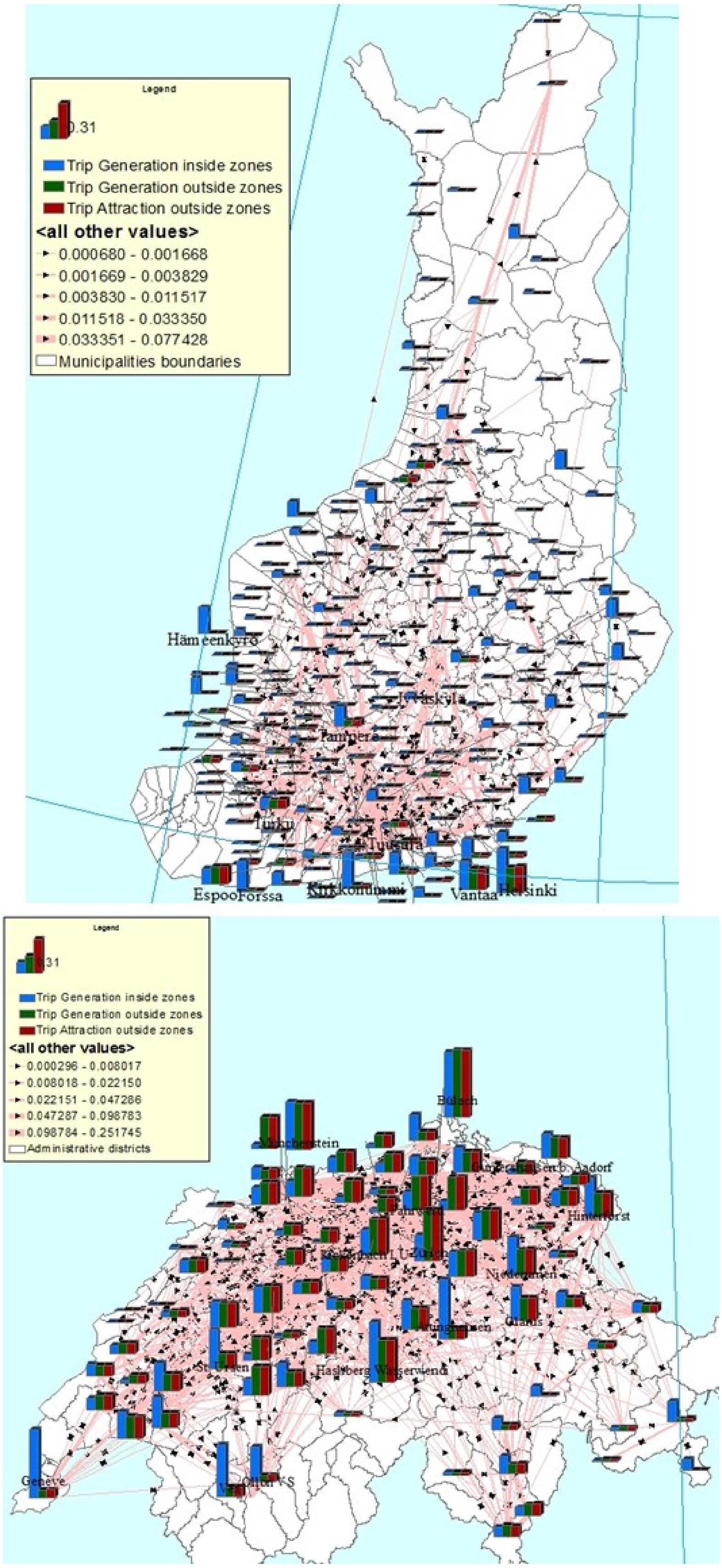


Figure 10. *Maps of travel survey data for 11-30 tons payload capacity based on trip generation and attraction in million trips.*

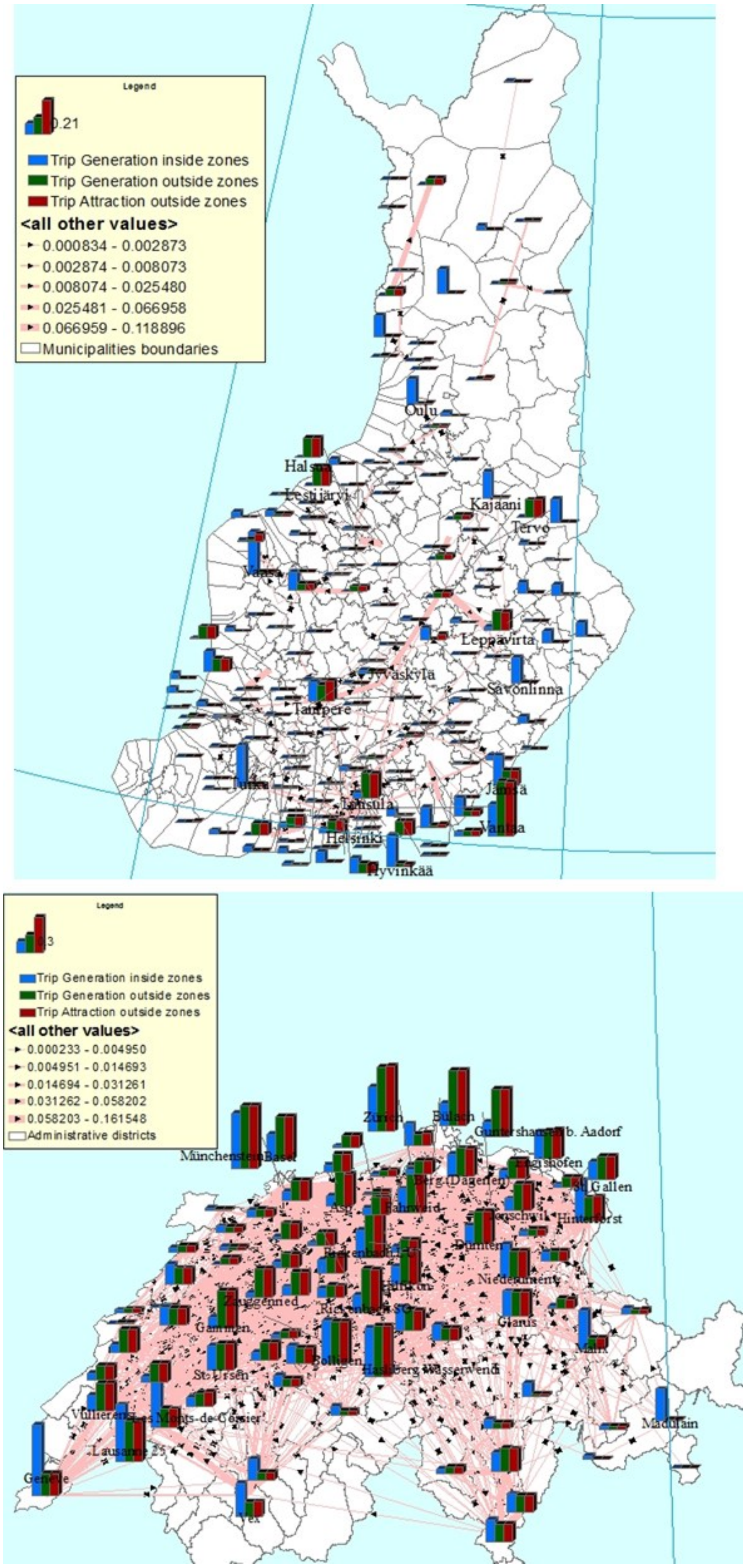


__Figure 11.__ Maps of travel survey data for up to 11 tons payload capacity based on trip generation and attraction in million trips.

The following notes provide important background information of map generation procedures which may be helpful to analyse the results. First, the maps are provided based on the zone size specification criterion, 2-digit postal codes in Switzerland, and municipality codes in Finland, discussed in Section 3.2.2 for both countries. Second, the inside and outside trip generation/attraction bar chart visualizations aim to provide a deeper insight into freight travel data. Third, the comparative maps are divided based on the payload capacity classifications defined in Chapter 3. More details of freight routing assignments may be discussed by analysis of important logistics centres' locations.

In Finland, the biggest trip generation/distribution centres are in the south and west of the country which are the most important international seaports and other important industrial cities connected by the national road networks. While in Switzerland, the biggest trip generation/distribution centres are in the north and west of the country which are connected by the national and international road networks. Switzerland has connected to neighbour countries such as France, Germany, Austria, and Italia by the means of road transport.

5.2 Simulation Results

5.2.1 Electric road scenario

Regarding the data summary of freight travel survey in Finland and Switzerland in Section 5.1 in this chapter, large proportion of freight in Finland is currently transported by trucks with more than 30 tons payload capacity. This freight classification, according to detailed discussion in Chapter 2, cannot be replaced by the current technology with the same size payload. As a result, according to the electric road alternative solution discussed in Chapter 2, the different electric road options like overhead line, rail, and inductive can be considered for electrifying freight transport of heavier payload capacity than 30 tons.

In this thesis, a generic form of electric road alternative solution, with no specification of the electric road option, is evaluated in scenario 2 in some highly demand routes in Finland. The following notes explain the analysis procedure for estimation of the successful trips in this electrification scenario.

First, the criterion for selecting routes are based on the most demanded heavy freight routes and distribution regions represented in the WSP Oy (2017) report and Figure 9. Accordingly, the most important regions are Helsinki, Vantaa, Espoo, Tampere, Oulu, Turku, Kotka, Lappeenranta, Seinäjoki, Lahti, Kouvola. As a result, 5 important routes are described and represented in Table 12 and Figure 12 as the most potential routes for electric road scenario in Finland.

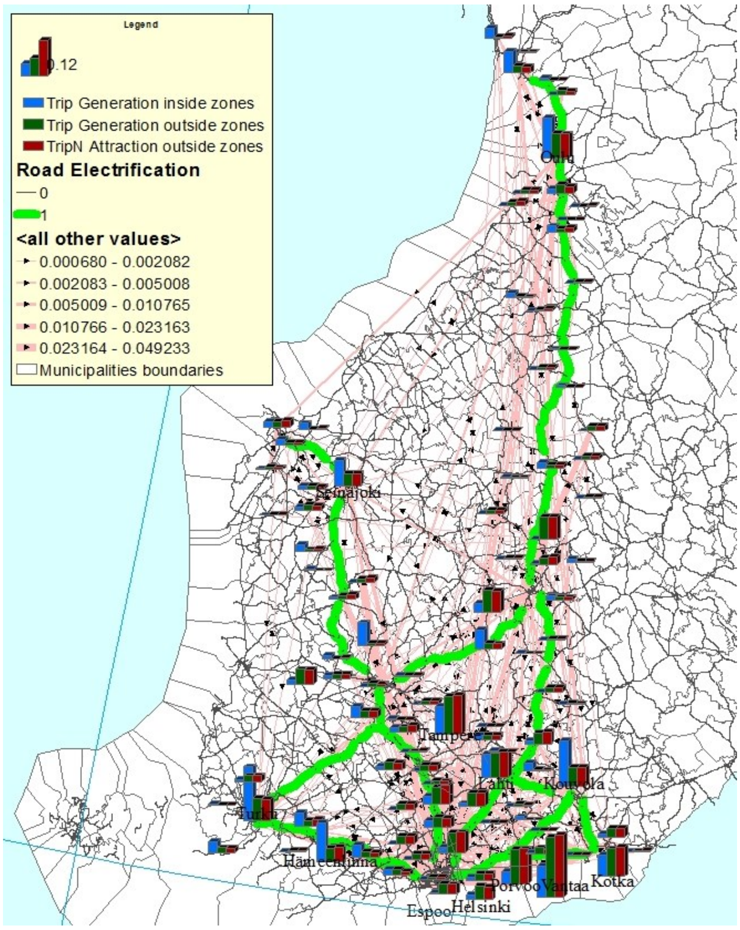


Figure 12. *Electric road scenario map in Finland based on trip generation and attraction in million trips.*

Table 12. *Summary data of the routes for electric road scenario in Finland based on the relevant ERSs infrastructures.*

Row No.	**Routes**	**Total length of two-way roads (km)**	**Total length of divided roads (km) (each direction)**
1	Helsinki-Porvoo-Kotka-Hammina-Kouvola-Lahti	305	610
2	Helsinki-Turku	165	330
3	Helsinki-Tampere-Seinäjoki-Vaasa	618	1,236
4	Helsinki-Lahti-Jyväskylä-Oulu-Kemi	825	1,650
5	Turku-Tampere-Jyväskylä	471	942
	Total	2,384	4,768

Second, all freight trips with payload capacity above 30 tons which were covered in 30 km radius neighbourhood of this route network, which is represented in Figure 12, is assumed as successful electrified freight trips in scenario 2 in Finland. The given 30 km range assumption with no charging possibility can be recovered by the home charging and the continuous charging by the ERSs. Therefore, all measures relevant to Figure 12 would be added to the BEVPO model results in scenario 2 (for the option with ERS).

Third, due to the limited resources in electric road cost estimation and high uncertainty level for different cost elements such as the power and infrastructure cost, the cost analysis of road electrification scenario is calculated according to Langhelle et al. (2018). Langhelle et al. (2018) conducted a broad conceptual study of electric roads for heavy goods transport in Norway and provided rough estimations for cost benefit analysis of electric road scenarios.

The electric road requires to have annual average daily traffic (AADT) more than 8-900 for being socio-economic profitable alternative solution for conventional heavy road freight transport. Accordingly, the cost estimation of 1.6 million euros per km construction of overhead line infrastructure can be used for the final action cost analysis of $CO_{2,eq}$ reduction (Langhelle et al. 2018). According to Langhelle et al. (2018), by the combination of 300 kWh battery capacity and 33% of distance charging via ERSs can be suitable for long trips by heavy-duty BETs. As a result, regarding the table, the cost of electric road infrastructures can be estimated at around 1,271 million euros for the overhead line type of the ERS's infrastructures.

5.2.2 BEVPO model results

All the scenario packages were analysed by BEVPO model for both countries. Regarding the delay time because of the online route assignment procedure by Google map API, the simulation procedure was time-consuming. As a result, the time for running the BEVPO model for different survey data sizes and payload capacity classes varied from 0.5 to 1 hours in Finland and 3 to 4 hours in Switzerland.

The primary results reported by the model were summarized and analysed by R programming tools. The R programming codes can be found at my GitHub account[1]. The primary results include charging activities, and the failed trips haulage shortage reports. Firstly, the R programming codes aimed to summarize all the relevant measures such as the total trip numbers, mileage, tonnage, tkm, fuel consumption, and relevant direct CO2 emission for each scenario package. Secondly, the R programming codes also aimed to cluster trips based on inside and outside zones for more advance analysis of results. Figure 13 illustrates comparative charts of successful trips in BEVPO model for Finland and Switzerland.

[1] https://github.com/MehdiJahangirSamet/O-D-and-Desire-lines-for-road-freight-transport-Finland-vs.Switzerland

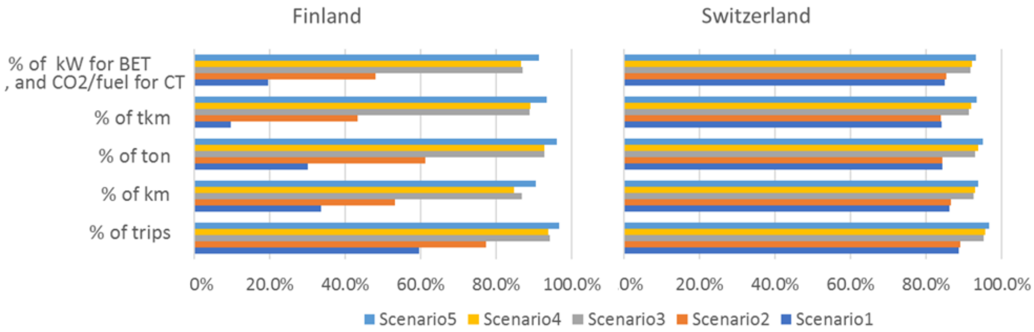


Figure 13. *Comparative analysis of successful trips in BEVPO model for Finland and Switzerland.*

The figure shows that the results of all the scenario packages in Switzerland are completely better than in Finland. By comparing Figure 13 and the results of the previous study with the same datasets, done by Liimatainen et al. (2019), the current results show great improvements for the potential trips electrification up to 20% and 80% in Finland and Switzerland, respectively. The reason behind such differences can root in the route assignment procedure applied in the BEVPO model.

In Finland, 60% of the trips can be electrified with BETs by using the current fast-charging facility locations. It must be noticed that all trips with payload more than 30 tons are failed because of the current battery technology limits discussed in previous chapters. However, the results are improved to 77% in scenario 2, mainly because of using ERS on some routes. The utilization of the ERS in some routes has led to the successful electrifying freight transport with payload above 30 tons under the current battery technology circumstances. In other scenarios, the electrification potential increases until to reach its pick, around 96%, in scenario 5. However, in Switzerland, scenario 1 and 2 have almost the same results with 89% electrification potential. In other scenarios, the electrification potential increases slightly until to reach its pick, around 97%, in scenario 5.

Clustering the failed trip results into the inside and outside origin-destination (O-D) zones or PLZs can give more insight into the travel survey data. Figure 14 and 15 illustrate the comparative charts of failed trips for BEVPO model in different PLZs and inside PLZs for Finland and Switzerland, respectively. Moreover, the figure illustrates the scenario 2 in Finland by consideration of the ERS scenario routes discussed in Section 5.2.1. If scenario 2 in Finland was without the ERSs, the electrifying potential would decline from 77% to 59% of the total trips.

Regarding Figure 14 and 15, the failed trips for scenario 1 and 2 in Finland are around 2 to 3 time those in Switzerland for both clusters of inside PLZs and between different PLZs. The reasons for such differences can be: (1) the different on-road charging facility network coverage, (2) and the accuracy of addressing system for O-D data. The first reason can be justified through the discussion of charging service area coverage of the on-road charging facilities in Section 3.2.1 in Chapter 3. The second reason will be justified by presenting the difference in the number of on-road charging activities which will be represented in Section 5.2.4.

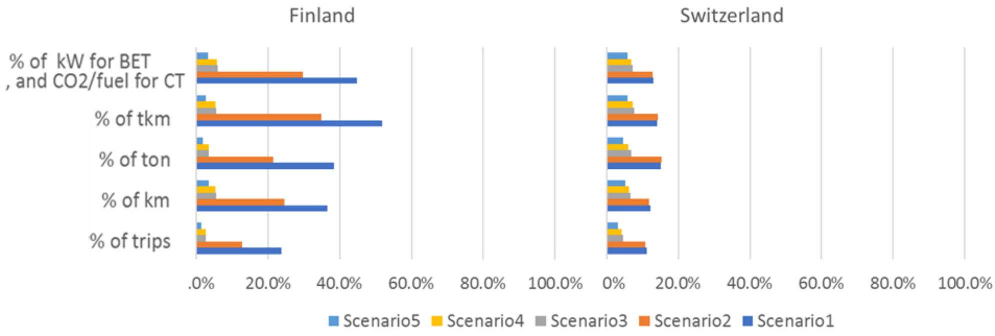


Figure 14. *Comparative analysis of failed trips in different PLZs in BEVPO model for Finland and Switzerland.*

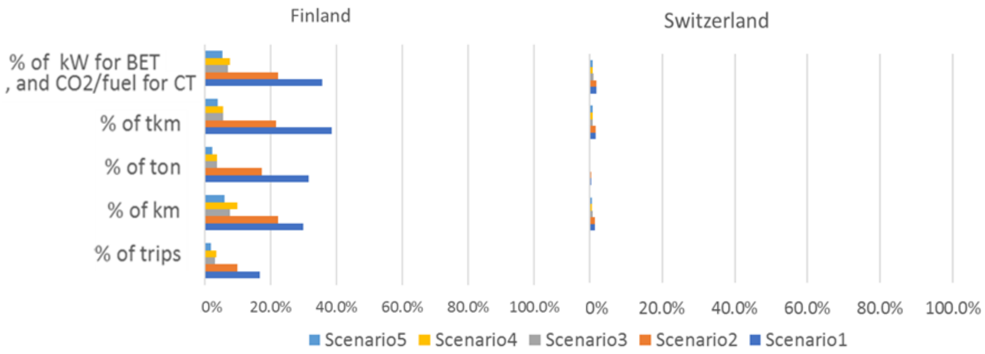


Figure 15. *Comparative analysis of failed trips inside PLZs in BEVPO model for Finland and Switzerland.*

However, the failed trips inside PLZs may turn into successful trips by managing the time schedules of freight trips and optimising the home charging facilities. As a result, optimistically, the number of the failed trips inside PLZs can be added to the successful trip results to make a new result named "the manageable successful trips". Figure 16 illustrates the comparative charts of the manageable successful trips in BEVPO model for both countries.

Figure 16 illustrates that the minimum electrification potential in Finland for all measures and scenario packages are around 50%. Whereas, in Switzerland, the minimum electrification potential is around 90%. For more advance comparative analysis, Figure 17 and 18 represent comparative charts of manageable successful trips by tkm% based on NTS2007 commodity groups and standard emission shares, respectively.

Figure 17 shows the variation of commodity groups' share for different scenario packages. The smallest electrification potential in Switzerland belongs to (03) mining and quarrying and (15) mail commodity groups with around 75%. Whereas, in Finland, the smallest electrification potential belongs to (19) unidentifiable goods with around 20%.

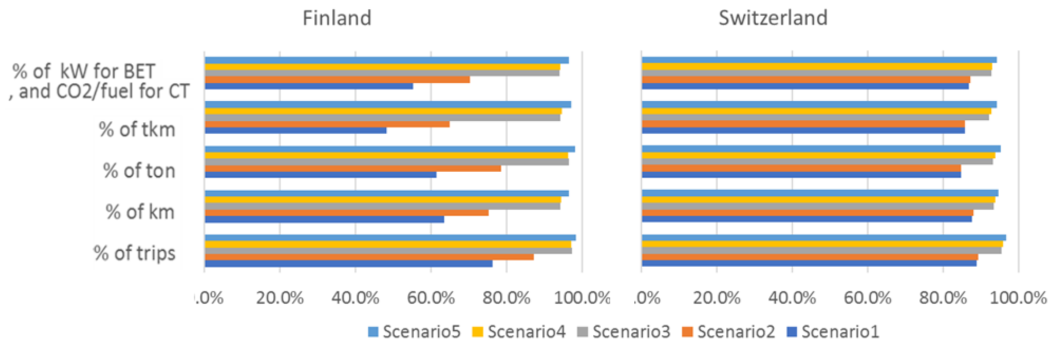


Figure 16. *Comparative analysis of manageable successful trips in BEVPO model for Finland and Switzerland.*

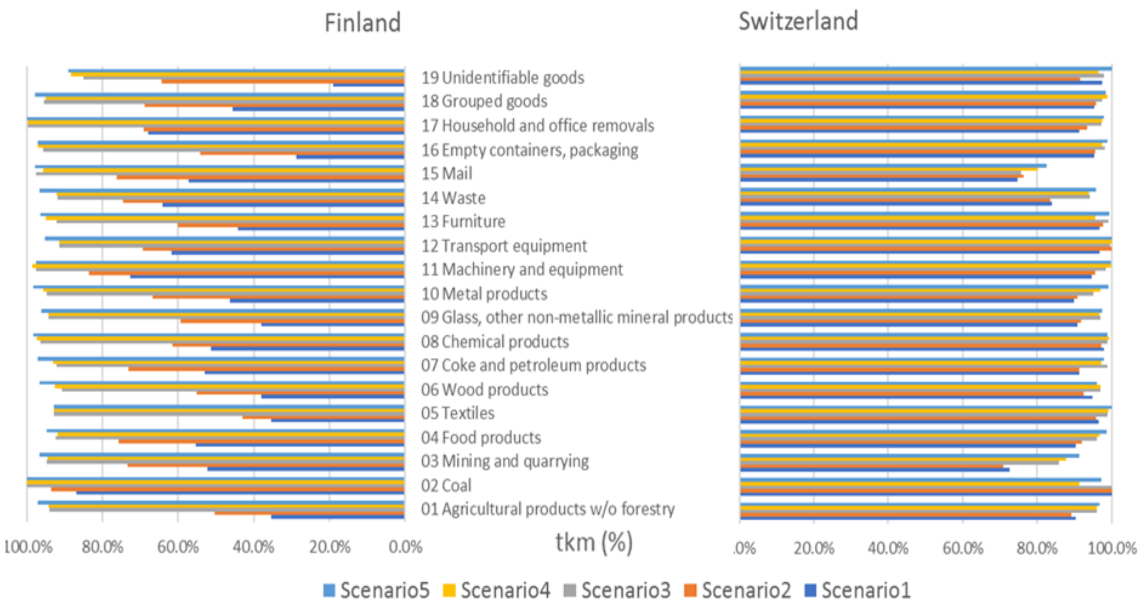


Figure 17. *Comparative analysis of manageable successful simulated trips in BEVPO model based on NTS2007 commodity groups.*

Figure 18 illustrates the variation of emission standards' share for different scenario packages. The smallest share in Finland is by Euro V and VI with around 40%. Whereas, in Switzerland, the smallest share is by Euro III, IV, V, and VI around 85%. Based on the comparative fuel consumption shares illustrated in Figure 7 in Section 5.1.1 for both countries, Euro V and VI emission standards has the biggest share of all travel survey data in both countries. Interestingly, Figure 18 also shows that the high electrification share of different scenarios for Euro V and VI emission standard share can subsequently duplicate the potential electrification improvements. To illustrate more details of the current electrification potential for different commodity types, Figure 19 shows the comparative charts of the commodity's share of total haulage and the electrification potential based on manageable successful results of scenario 1 in both countries.

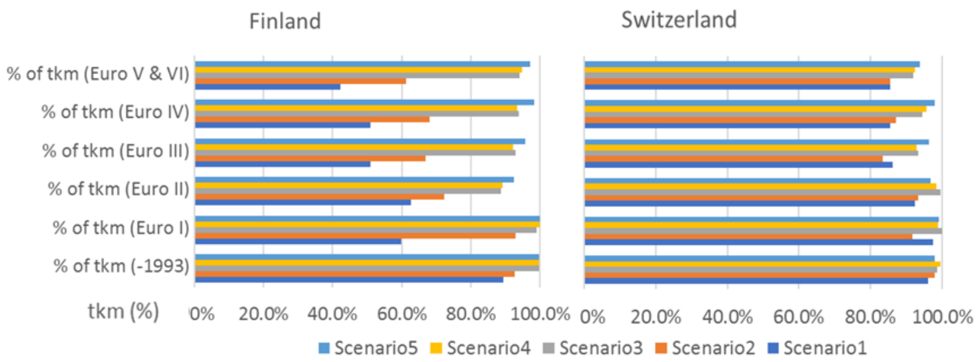


Figure 18. *Comparative analysis of manageable successful simulated trips in BEVPO model based on European emission standards.*

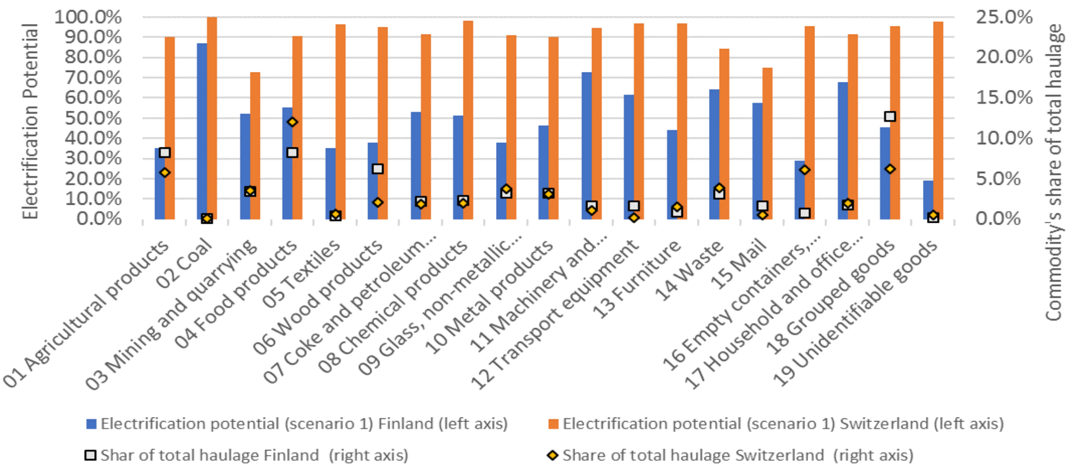


Figure 19. *Comparative analysis for the share of total haulage and electrification potential in current technology scenario based on manageable successful trip results in Finland and Switzerland.*

The figure shows that the range of electrification potential based on manageable successful trip results would change from 20% to 85% and 70% to 100% for Finland and Switzerland based on the current technology, respectively. Moreover, in Finland, the biggest share of the total haulage is by (18) grouped goods with around 12% which accounted for around 40% electrification potential. Whereas, in Switzerland, the biggest share of total haulage is by (04) food products with around 12% which accounted for 90% electrification potential.

5.2.3 Extended range solution

Regarding the discussion in Section 2.4 in Chapter 2, some parts of failed electrified trips, due to the range shortage of battery charge status, can be converted by the utilization of extended range BETs. The range covered by range-extenders technology and its relevant fuel type will play major roles to choose the best option. For example, a larger proportion of failed trips can be converted by increasing the range covered by range-extenders technology. Moreover, the results can be improved by using greener diesel fuel like biofuels. The shortage length of the failed trips in current technology scenario (scenario 1), were analysed based on different measures in both countries. Figure 20 illustrates comparative charts for the potential improvement of freight measures by using the extended range technology for payload capacity up to 30 tons in both countries.

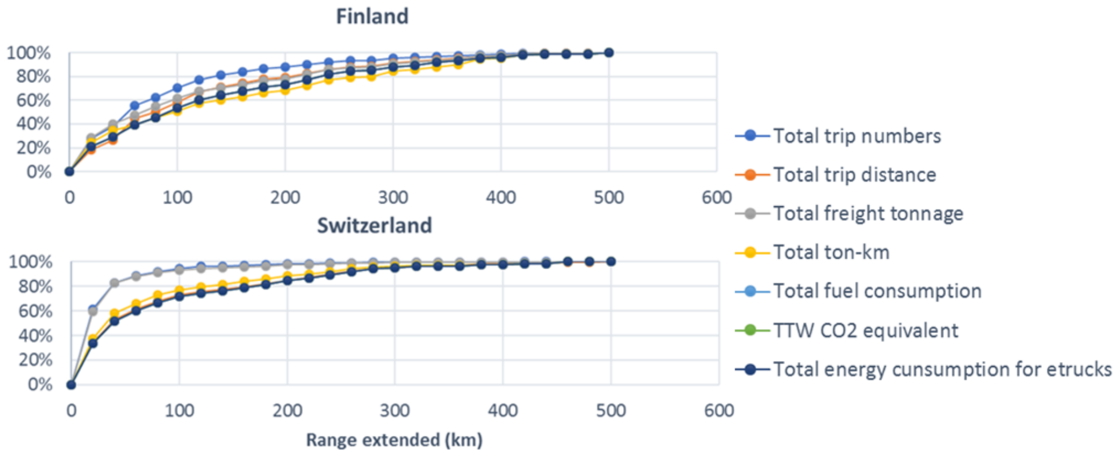


Figure 20. *Comparative analysis for potential improvement of freight measures by using extended range technology for payload capacity up to 30 tons in Finland and Switzerland.*

The figure shows that the potential improvement in Switzerland is higher than in Finland. For example, regarding the figure, around 60% and 80% of the failed trips in Finland and Switzerland, respectively, can be covered by using an extended range technology covering 100 km. The following notes can help to use other measures represented in the figure.

The change in TTW $CO_{2,eq}$ fuel consumption, and relevant kWh energy consumption measures will be considered if the extended range technology is accompanied by the increase of the gravimetric energy density for the battery in the future. If the scenario of extended range technology is based on the typical diesel fuel consumption solutions these figures will not be considered as an improvement.

Therefore, the measures like the trip number, trip distance, freight loads, and tkm can be considered as improvement measures in such extended range solutions. For the evaluation of other fuels like diesel biofuels, the given measures must be calculated accordingly. There is no doubt that the utilization of cleaner fuel types in extended range technology solutions can improve emission measures.

5.2.4 Charging activities

The roadway charging activities resulted from the BEVPO model are analysed by R programming. The charging activities of different scenario packages in BEVPO model are represented in GIS maps in Figure 21 which can be helpful for resource allocation of the on-road fast charging facilities.

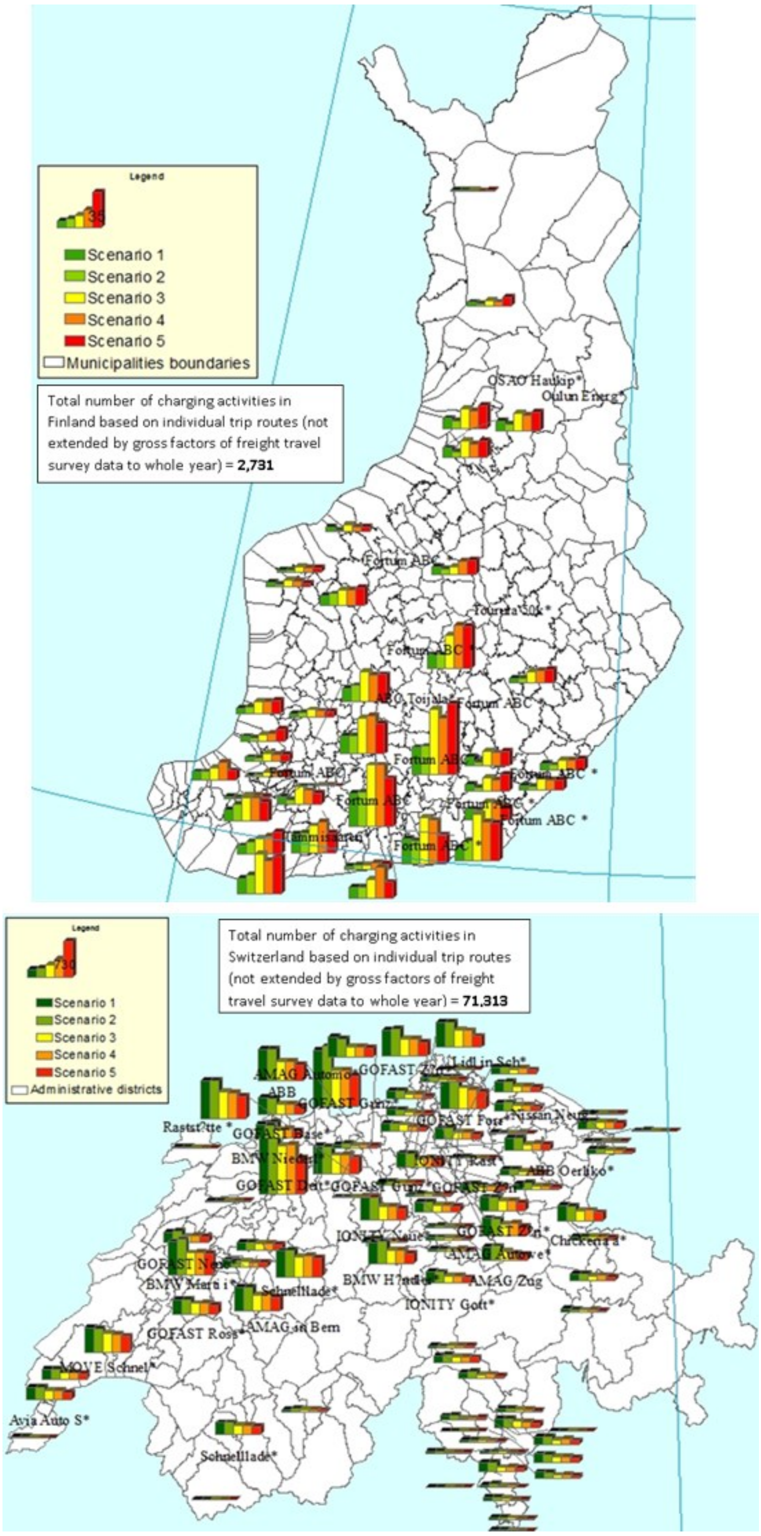


Figure 21. *Comparative analysis of on-road charging activities based on BEVPO results (the number of charging activities per on-road charging facilities).*

The figure shows that the total number of on-road charging activities, based on individual trip simulation in BEVPO model and not extending by gross factors to the whole year data, in Switzerland (71,313) is significantly higher than in Finland (2,731). The reason can root back to the accuracy of the addressing system and the O-D data of freight demand applied in Finland's O-D data. Regarding the methodology of travel data preparation described in Section 3.2.2, the O-D data in Finland are summarized by postal codes within a municipality code. This may reduce the accuracy of the results for route assignments using Google map APIs. Since the default addressing systems in Google map APIs is set based on more accurate addressing methods by postal codes.

The figure shows that the charging facilities in scenario 1 and 2 are less than other scenarios in Finland. Whereas, in Switzerland, the trend is inverse and most of the charging activities in scenario 3, 4, and 5 are smaller than the first two scenarios. The results can be explained by the following hypotheses. In Finland, the coverage of roadway charging facilities is low and by improving the battery technology and fast charging facilities in scenario packages of 3, 4, and 5, the longer-haul trips can get the chance of recharging. Whereas in Switzerland, the coverage of roadway charging facilities is high and by improving the battery technology and fast charging facilities in scenario packages of 3, 4, and 5, there are fewer needs for recharging of the longer-haul trips.

5.3 Life Cycle Assessment

Regarding the methodology of LCA calculation described in Chapter 4, the successful trip results of different scenario packages are analysed for CTs and BETs alternatives. In order to simplify the analysis procedures and focus more on the LCA, the manageable successful trip results would not be discussed in this section. The required numbers of BETs are calculated based on the average annual mileage of different payload classification groups represented in Table 3 in Chapter 3. The given numbers are applied for the LCA of different scenario packages which resulted in the total life cycle mileage of battery packs varies from 151,480 to 301,388 km and from 248,208 to 257,080 km in Finland and Switzerland, respectively. Accordingly, Figure 22 illustrates comparative charts of total annual LCA and the potential LCA reduction of successful trip results for different scenario packages in both countries.

The left axes show the total annual $CO_{2,eq}$ LCA in k tons including the WTW and additional $CO_{2,eq}$ emission divisions which are represented by the column charts for each scenario package. The right axes show the annual LCA reduction potential of the electrification scenario packages by diamond symbols based on the measures represented in left axes.

On the one hand, regarding Figure 22, the annual total WTW $CO_{2,eq}$ emission in Finland for medium and heavy-duty diesel CTs is 2.5 million tons for the current scenario which can be reduced up to 80% (0.50 million $CO_{2,eq}$ tons in scenario 5) by using BETs. While the annual total WTW $CO_{2,eq}$ emission in Switzerland for medium and heavy-duty diesel CTs is 1.67 million tons and can be reduced up to 91% (0.15 million $CO_{2,eq}$ tons in scenario 5) by using BETs.

On the other hand, the annual total additional $CO_{2,eq}$ emission in Finland for medium and heavy-duty diesel CTs is 0.12 million tons for the current scenario which can increase up to 13 times (1.6 million $CO_{2,eq}$ tons in scenario 5) by using BETs. While the annual total additional $CO_{2,eq}$ emission in Switzerland for medium and heavy-duty diesel CTs is 0.09 million tons and can be increased up to 10 times (0.88 million $CO_{2,eq}$ tons in scenario 5) by using BETs.

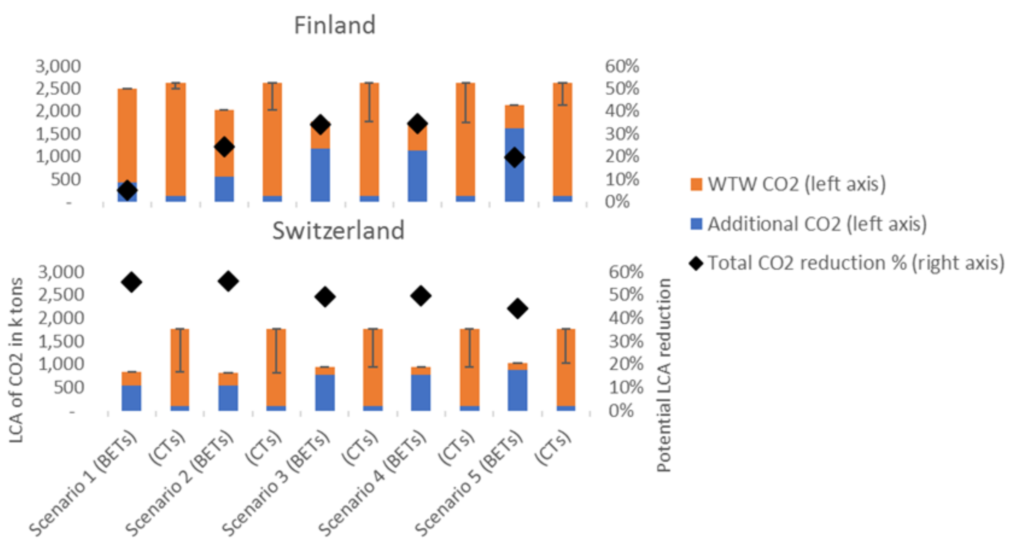


Figure 22. *Annual LCA reduction potential for successful trips in Finland and Switzerland.*

In addition, in Finland, the BETs option in scenario 3 and 4 have the largest annual LCA reduction, while the BETs option in scenario 1 has the lowest annual LCA reduction compared to the CTs option. In Switzerland, the BETs option in scenario 1 has the largest annual LCA reduction potential and the BETs option in scenario 5 has the lowest annual LCA reduction potential compared to the CTs option.

As it is discussed in Section 4.2 in Chapter 4, the size of the battery can play a major role in the amount of additional $CO_{2,eq}$ emission for the BETs option. The trend of potential LCA reduction can be interpreted in two terms. Firstly, the increase of additional $CO_{2,eq}$ emission in BETs for the scenario packages with bigger battery size leads to the increase of the annual LCA. Secondly, the increase of the electrification potential leads to the increase of LCA simultaneously.

Sensitivity analysis of mixed grid electricity generation

Regarding the methodology described for the LCA in Section 4.1 and 4.2 in Chapter 4, uncertainty ranges in many factors such as fuel consumption formula, direct emission, and the supply chain-related emission of fuel can impact directly or indirectly on the final LCA measures. However, many of these assumptions are as a part of the calculation procedure which is mainly adopted from multiple resources. They could be evaluated through very detailed sensitivity analyses, which is off the topic for this thesis.

However, the role of mixed grid electricity generation change in the potential LCA improvement in this thesis cannot be neglected. The different energy policies and strategies such as the reduction of $CO_{2,eq}$ emission per kWh of mixed grid electricity generation can have a direct impact on different sub-sectors such as electrifying road freight transport. The impact can be analysed through sensitivity analysis of the potential LCA reduction based on +/- 50% variation of the default emission measures from the mixed grid electricity generations of Finland and Switzerland in Chapter 3. Figure 23 represents comparative charts of the sensitivity analysis for the potential LCA reduction of different scenario packages based on the emission changes of the mixed grid electricity generation for the successful trip results in both countries.

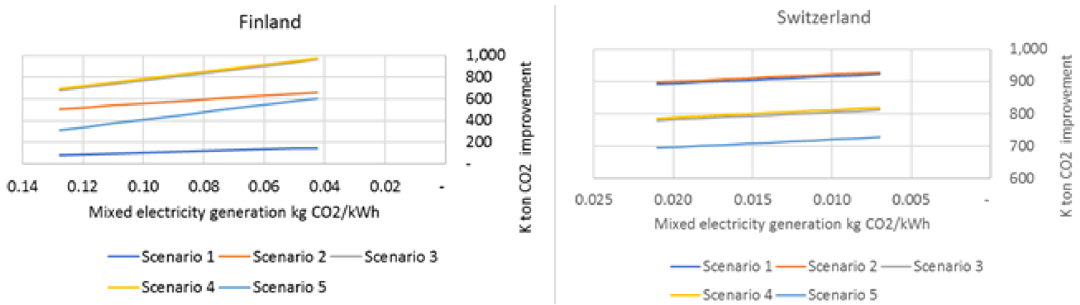


Figure 23. *Sensitivity analysis for potential LCA improvement of successful trips by the emission changes of the mixed grid electricity generation.*

The figure reflects that in Finland, scenario 4 with totally green electricity generation source for successful trip results could be the maximum $CO_{2,eq}$ reduction potential by the 1.148 million tons $CO_{2,eq}$. Whereas in Switzerland, scenario 2 with green electricity generation source for successful trip results could be the maximum $CO_{2,eq}$ reduction potential by 0.964 million tons $CO_{2,eq}$.

5.4 TCO results

Regarding the methodology described for the TCO calculation procedure in Section 4.3 in Chapter 4, different cost elements of the TCO are calculated for different scenario packages of BETs and CTs for ten years. Figure 24 shows the TCO change potential for successful trips in Finland and Switzerland.

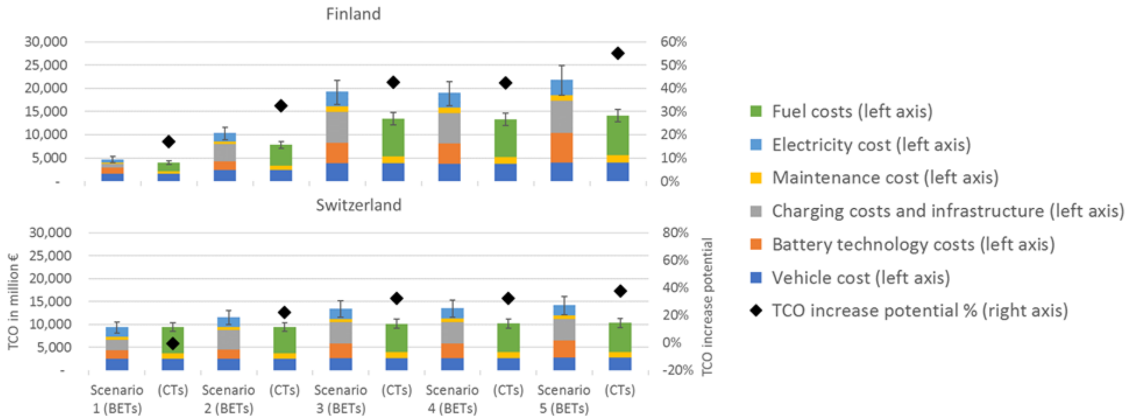


Figure 24. *TCO change potential for the successful trips in Finland and Switzerland.*

The figure represents comparative charts of the total TCO and relevant potential change of electrification scenario packages for both countries. The left axes illustrate the total TCO in million euros for different scenario packages of BETs and CTs. Whereas, the right axes illustrate the potential change of electrification freight transport for different scenario packages based on the data represented in the left axes. The uncertainty range of the total TCO due to different uncertainty parameters, based on the detail discussions in Section 4.3 in Chapter 4, are represented by line limits over the column charts. The potential of the total TCO for road freight transport in both countries increase by the improvement of battery technology and fast charging facilities. This trend can be explained by the following notes.

First, the increase in battery costs due to the larger battery capacities in different scenario packages has a direct impact on the increase of the total TCO. Second, the increase of the potential successful trips in scenario packages with the larger battery capacities intensifies simultaneously the total TCO. As a result, the total TCO and the TCO increase-potential of electrification raise by the increase of the battery capacities in different scenario packages. On the one hand, the results show that the least expensive electrification scenario package is scenario 1 for both countries. Accordingly, in Finland, the TCO for electrification increase 17% compare to the conventional trucks. Surprisingly, in Switzerland the relevant electrification scenario, scenario 1, even leads to 0.5% reduction in TCO compared to the conventional trucks. On the other hand, the most expensive electrification scenario package is scenario 5 for both countries which leads to 55% and 37% increase in the TCO for Finland and Switzerland, respectively.

TCO sensitivity analysis

Regarding the methodology described for the TCO calculation in Section 4.3 in Chapter 4, uncertainty ranges of different cost elements such as vehicle cost, battery technology cost, charging and infrastructure cost, maintenance cost, fuel price, and discount ratio can change the TCO. The following tables illustrate the TCO sensitivity analysis based on the selected cost elements change in Finland and Switzerland.

The given uncertainty ranges are based on low and high-cost scenarios defined in Section 4.3 in Chapter 4. Except for some minor differences in some results, the tables represent very close results in both countries.

Table 13. *TCO sensitivity analysis based on cost elements change in Finland.*

TCO uncertainty range in different scenarios / Uncertainty in different cost elements	Uncertainty range ±(%)		Scenario 1 ±(%)		Scenario 2 ±(%)		Scenario 3 ±(%)		Scenario 4 ±(%)		Scenario 5 ±(%)	
	BETs	CTs	BETs	CTs	BETs	CTs	BETs	CTs	BETs	CTs	BETs	CTs
Vehicle cost	10	10	3.4	4.0	2.2	2.9	1.9	2.7	1.9	2.7	1.7	2.7
Battery technology cost	30	0	6.3	0	4.2	0	5.3	0	5.3	0	6.7	0
Charging and infrastructure cost	10	0	1.6	0	3.5	0	3.4	0	3.5	0	3.2	0
One-time cost	50	10	11.2	4.0	9.9	2.9	10.6	2.7	10.6	2.7	11.6	2.7
Maintenance cost	10	10	0.7	1.4	0.6	1.2	0.6	1.1	0.6	1.1	0.5	1.1
Fuel price	10	10	1.5	4.5	1.7	5.7	1.7	6.0	1.7	6.0	1.5	6.0
Discount ratio	50	50	2	6.5	2.2	7.6	2.1	7.9	2.1	7.9	1.9	7.9

Table 14. *TCO sensitivity analysis based on cost elements change in Switzerland.*

TCO uncertainty range in different scenarios / Uncertainty in different cost elements	Uncertainty range ±(%)		Scenario 1 ±(%)		Scenario 2 ±(%)		Scenario 3 ±(%)		Scenario 4 ±(%)		Scenario 5 ±(%)	
	BETs	CTs	BETs	CTs	BETs	CTs	BETs	CTs	BETs	CTs	BETs	CTs
Vehicle cost	10	10	2.6	2.6	2.1	2.6	1.9	2.6	1.9	2.6	1.9	2.6
Battery technology cost	30	0	4.8	0	3.9	0	5.4	0	5.4	0	6.0	0
Charging and infrastructure cost	10	0	2.3	0	3.7	0	3.4	0	3.4	0	3.3	0
One-time cost	50	10	9.6	2.6	9.7	2.6	10.7	2.6	10.7	2.6	11.2	2.6
Maintenance cost	10	10	0.8	1.2	0.6	1.2	0.6	1.2	0.6	1.2	0.6	1.2
Fuel price	10	10	2.2	6.1	1.8	6.1	1.7	6.1	1.7	6.1	1.6	6.1
Discount ratio	50	50	2.8	8.1	2.3	8.1	2.1	8.2	2.1	8.2	2.0	8.2

Regarding the tables, the discount ratio has the largest uncertainty impact on the total TCO for CTs. While the one-time cost is accounted as the largest uncertainty impact on the total TCO for BETs. The one-time cost includes the vehicle, battery and charging and infrastructure cost elements.

Moreover, the uncertainty range of the battery technology costs in BETs and fuel price in CTs options would result in the second-largest uncertainty range of the total TCO. Finally, the uncertainty range in other cost elements has led to smaller changes, less than 4%, of the total TCO in both countries.

The results of the TCO analysis based on Figure 24 show that the battery pack cost of 160 €/kWh for battery pack capacities of 190-330 kWh, and 4 years battery lifetime (with battery life cycle mileage variation of 248,208-257,080 km) can turn the BETs to an economically viable option compared to CTs in Switzerland, in scenario 1. The results also show that in Finland, according to the sensitivity analysis of TCO for the current battery technology and charging facilities, the relevant price of battery pack capacities of 190-330 kWh, and 4 years battery lifetime (with battery life cycle mileage variation of 151,480-301,388 km) can be calculated around 86 €/kWh (with 46% reduction in battery costs), in scenario 1.

5.5 Action costs and abatement costs analysis for GHG reduction potential

On the one hand, the action costs for $CO_{2,eq}$ LCA reduction are calculated, based on the definitions provided in Section 4.4 in Chapter 4, for different scenario packages for successful trips in Finland and Switzerland. Table 15 shows the relevant $CO_{2,eq}$ LCA reduction results for different scenario packages for successful trips in Finland and Switzerland.

Table 15. *Action costs for $CO_{2,eq}$ LCA reduction in different scenario packages for successful trips in Finland and Switzerland.*

Action Costs for CO2 reduction (in €/ton)	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Finland	371	550 (613*)	540	522	1,250
Switzerland	-5	348	404	403	528
* Without the electric road system					

Table 15 shows that the most cost-efficient scenario package for $CO_{2,eq}$ LCA reduction in Switzerland is Scenario 1 which is accounted for -5 €/ton. The negative action costs for $CO_{2,eq}$ LCA reduction means that the benefits is more than the costs. This means that the relevant electrification scenario leads to save 5 €/ton $CO_{2,eq}$ in Switzerland compared to the conventional trucks. Whereas, in Finland the least action costs for $CO_{2,eq}$ LCA reduction belongs to scenario 1 with 371 €/ton $CO_{2,eq}$. Interestingly, the relevant action costs for $CO_{2,eq}$ LCA reduction by using the overhead line option for the ERS alternative reduces by 10% (550 €/ton $CO_{2,eq}$) compared to not using the ERS.

On the other hand, the $CO_{2,eq}$ abatement costs are calculated based on formula represented by Berger (2016) which only consider the WTW $CO_{2,eq}$ emission reduction. Table 16 represents $CO_{2,eq}$ abatement costs in different scenario packages for successful trips in Finland and Switzerland.

The table represents slighter fluctuations between different scenario packages compared to the previous cost-efficiency measure in Table 15. As it is discussed before, the battery capacity intensifies the difference of additional $CO_{2,eq}$ emission between different scenario packages. As a result, the $CO_{2,eq}$ abatement costs in the table represent smaller changes between different scenario packages compare to the action costs for $CO_{2,eq}$ LCA reduction. The results in the table will be discussed more in the next chapter for comparing the other potential cost-efficient alternative solutions of decarbonising road freight transport.

Table 16. *$CO_{2,eq}$ abatement costs in different scenario packages for successful trips in Finland and Switzerland.*

Action Costs for CO2 reduction (in €/ton)	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Finland	106	317 (188*)	243	240	310
Switzerland	-3	234	221	221	255

* Without the electric road system

To facilitate the comparative analysis, the potential $CO_{2,eq}$ LCA reduction represented in Figure 22 and the action costs of $CO_{2,eq}$ LCA reduction represented in Table 15 are combined to generate Figure 25. The best alternative scenario package can be selected based on the measures represented in this figure. Moreover, regarding the potential improvement of battery and fast charging technology, the short and long-term horizons can be proposed in both countries.

The left axis in the figure represents the action costs for $CO_{2,eq}$ LCA reduction in €/ton for different scenario packages, illustrated by column charts, in Finland and Switzerland. While the right axis represents the LCA reduction potential, illustrated by squares in Finland and Switzerland. In Finland, for the short-term horizon, scenario 2 with overhead line ERS alternative solution is the best option by 24% reduction per year, which accounted for 0.603 million tons $CO_{2,eq}$ with the action costs of 550 €/ton. Whereas, for the long-term horizon, scenario 4 is the best option by 35% reduction per year, which accounted for 0.869 million tons $CO_{2,eq}$, with the action costs of 522 €/ton. On the contrary, in Switzerland, for both short and long-term horizon, scenario 1 is the best option by 56% in LCA reduction per year, which accounted for 0.928 million tons $CO_{2,eq}$ with the saving action costs of 5 €/ton.

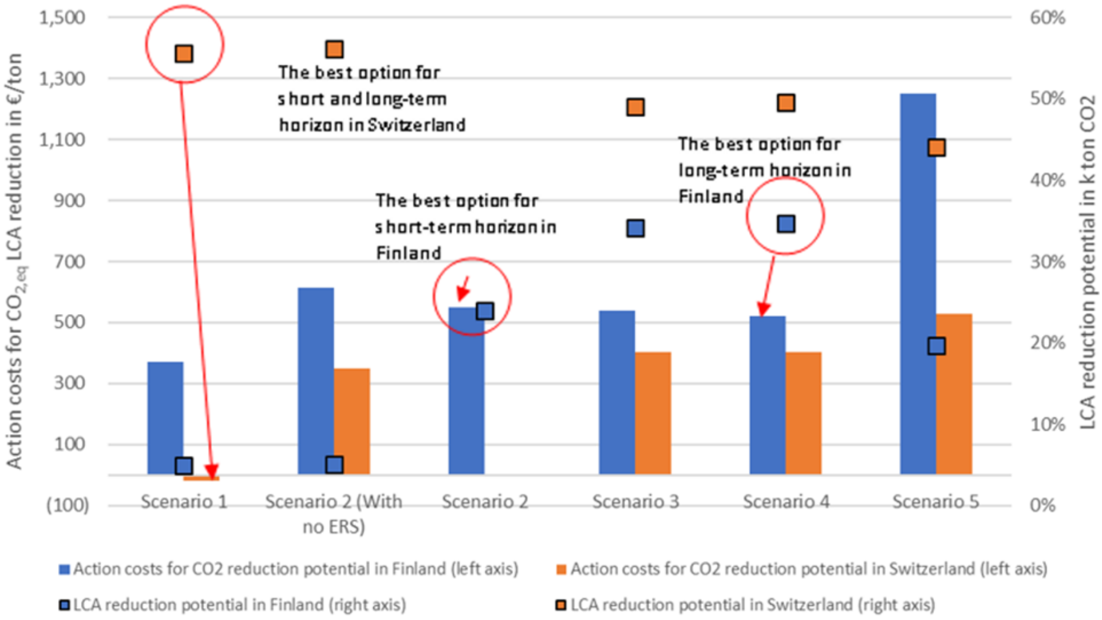


Figure 25. *$CO_{2,eq}$ LCA reduction potential and the action costs.*

The results show that the action costs for $CO_{2,eq}$ LCA reduction based on the best electrification scenario package in Switzerland is smaller than the relevant measures in Finland. Moreover, the potential reduction of LCA in Switzerland is higher than in Finland. It must be noticed that if the given numbers are aimed be used for the future planning, the future growth for freight demand and the market entrance situation for the BET technology adoption must be also considered.

6. LESSONS LEARNT AND DISCUSSION

This chapter aims to summarize and discuss the results and analyses in this thesis. Accordingly, in Section 6.1, the answers for sub-research and main questions represented in the introduction are provided. In Section 6.2, further discussions would be provided relevant to the other important results, limitations, and future suggestions.

6.1 Answers for the research questions

What share of road freight trips can be successfully covered with the currently available BETs models and the current charging infrastructures in Finland and Switzerland?

In Finland, 60% of all road freight trips, which cover 10% of all tkm, by medium and heavy-duty trucks can be transported by the current technology of BETs and the fast-charging possibility (based on the current public fast-charging facility locations). While, in Switzerland, the electrification potential for the same freight payload classification and under the same fast-charging conditions is estimated to be around 89% which cover over 84% of all tkm. The results clarify that the electrification potential under the current technology limits is very low in Finland. On the contrary, the electrification potential under the current technology limits is very high in Switzerland.

Additionally, the results show 20% and 70% growth in the number of electrified trips potential compared to the results of Liimatainen et al. (2019) with the same datasets in 2016 for Finland and Switzerland, respectively. However, the growth rate for the relevant tkm measure is much bigger, around 67% and 460% for Finland and Switzerland, respectively.

The difference may mainly be concerned with the accuracy of the routing assignment via using Google map direction API in the BEVPO model. The other reasons for such differences might be the small differences in the details of battery capacity and the daytime charging powers. In the previous study, the on-road charging power in the daytime was 50 kW, while, in this study, the on-road charging power during the day is assumed to be distributed 50-50% by 50 and 120 kW. Moreover, in the previous study, the battery capacities of 150 and 400 kWh were assumed for the rigid and articulated BETs, respectively. While in this study the battery capacities are assumed 120 to 435 kWh for the rigid and articulated BETs, respectively.

How much the improvement of BETs range and charging infrastructure can raise the share of successful BETs trips in Finland and Switzerland?

In addition to a scenario defined for the current technology, four different scenarios were defined for evaluating the impact of the different BETs range and charging infrastructure improvement on the electrification potential. Accordingly, the battery capacity with 75% increase and the possibility of access to the ultra-fast charging with the 450-kW power lead to 60% trips (1000% tkm) and 9% trips (10% tkm) improvement in the electrification potential for Finland and Switzerland, respectively. However, the best results for electrification potential based on the electrification technology improvements are the same, around 97% trips (93% tkm), for both countries.

What other alternative or/and complementary solutions could be proposed for the electrifying road freight in Finland and Switzerland?

The ERSs in some routes in Finland can be a complementary solution for the heavy-duty truck electrification with the current battery technology limits. Accordingly, the electrification potential concerned with the ERS in some routes is estimated at around 77% trips (43% tkm) which means 28% trips (350% tkm) increase compared to the current technology potential scenario. Other alternative solutions such as using different range-extenders and battery-swapping technologies are recommended to increase the electrification potential in both countries. The given complementary solutions can help to relieve the possible economic and range anxieties related to BEV adoption. But, estimation of their impact for electrification potential is out of the scope of this thesis.

What are the road freight transport range needs in Finland and Switzerland?

The range needs are concerned with the battery technology limits as well as the fast-charging facilities based on the different payload capacities. First, in terms of the payload capacity, Switzerland is more suitable for the road electrification with the current battery technology compare to Finland. This is mainly because of the road freight limit for maximum GVW is 40 and 76 tons in Switzerland and Finland, respectively.

Moreover, the O-D data for the road freight trips and the road network size in Switzerland led to shorter range needs compare to Finland. In addition, the sensitivity analysis for the extended range potential shows that a larger improvement for the potential electrification in Switzerland can be achieved by the smaller range improvement compared to Finland.

Finally, the action costs for $CO_{2,eq}$ LCA reduction potential as well as the electrification potential for choosing the best electrification scenario would determine the specified range needs in each country for different horizons. The last sub research question about choosing the best scenario packages would explain the range specifications in each country for both short and long-term horizons.

What could be the amount of $CO_{2,eq}$ WTW emissions in different scenario packages of battery technology and charging infrastructures in BETs in Finland and Switzerland? And how does it compare to the conventional diesel truck?

The WTW $CO_{2,eq}$ emission would be dropped dramatically by electrifying the road freight, particularly, when the source of electricity generation is green. Regarding the road freight transport data of the medium and heavy-duty trucks in Finland and Switzerland in 2016, the total annual WTW $CO_{2,eq}$ emission generated by diesel CTs in Finland is 1.5 times that in Switzerland. However, the BETs can promote up to 80% and 91% reduction in the total annual WTW $CO_{2,eq}$ in Finland and Switzerland, respectively. This can be interpreted to the total annual WTW $CO_{2,eq}$ emission reduction around 2 and 1.54 million tons in Finland and Switzerland, respectively.

What could be the amount of $CO_{2,eq}$ emissions aside from WTW emissions in different scenario packages of battery and charging infrastructures in BETs in Finland and Switzerland? And how does it compare to the conventional diesel truck?

Contrary to WTW $CO_{2,eq}$ emission, the additional $CO_{2,eq}$ emission would increase by electrifying the road freight. The main reason is that the $CO_{2,eq}$ emission related to battery production is significantly high. The additional $CO_{2,eq}$ emission value aggravates when the battery capacity increases. Regarding the road freight transport data for the medium and heavy-duty trucks in Finland and Switzerland in 2016, the annual total additional $CO_{2,eq}$ emission generated by diesel CTs in Finland is 1.3 times that in Switzerland. However, the annual total additional $CO_{2,eq}$ by BETs can be scaled up to 13 and 10 times as big as the one by diesel CTs in Finland and Switzerland, respectively. This can be interpreted to the annual total WTW $CO_{2,eq}$ emission raises around 1.5 and 0.79 million tons in Finland and Switzerland, respectively.

What could be the $CO_{2,eq}$ reduction potentials in Finland and Switzerland using life cycle assessment (LCA) approach?

Regarding the comparative analysis of WTW and additional $CO_{2,eq}$ emissions between diesel CTs and BETs in Finland and Switzerland, the $CO_{2,eq}$ LCA reduction potential varies based on the scenario packages defined in Section 3.2.4 in Chapter 3. On the one hand, the largest potential of total $CO_{2,eq}$ LCA reduction in Finland belongs to scenario 3 and 4, with around 35% which is accounted for 0.86 million tons $CO_{2,eq}$ per year. Both scenario 3 and 4 have had the battery capacity increase of 50%. Moreover, the power of fast charging facilities has been increased to 250 and 350 kW in scenario 3 and 4, respectively.

On the other hand, the largest potential of total $CO_{2,eq}$ LCA reduction in Switzerland belongs to scenario 1 and 2, with around 56% which is accounted for 0.93 million tons $CO_{2,eq}$ per year. Both scenario 1 and 2 have had the current battery technology capacity limits. Moreover, the power of fast charging facilities has been increased to 150 kW only in scenario 2.

What could be the total cost of ownership (TCO) in BETs for different scenario packages of battery and charging infrastructures compared to the TCO of the diesel CTs in Finland and Switzerland?

The TCO would be increased usually by electrification of road freight transport. The main reason is that the cost of battery production is significantly high. The TCO aggravates when the battery capacity increases. Regarding the road freight transport data of the medium and heavy-duty trucks in Finland and Switzerland in 2016, on the one hand, the minimum increase of TCO for electrifying road freight belongs to scenario 1 in both countries. In Finland, the relevant TCO measure in BET option increases 17% compared to CT one. However, in Switzerland, the relevant TCO measure in BET option exceptionally reduces 0.5% compared to CT one. On the other hand, the most expensive electrification scenario package, which are the ones with the bigger battery capacities, belongs to scenario 5 with around 55% and 37% increase in Finland and Switzerland, respectively.

What could be the action costs for $CO_{2,eq}$ reduction in different scenario packages of battery and charging infrastructures in BETs in Finland and Switzerland?

Regarding the comparative analysis of LCA and TCO between diesel CTs and BETs in Finland and Switzerland in previous discussions, the action costs for $CO_{2,eq}$ LCA reduction varies based on the scenario packages defined in Section 3.2.4 in Chapter 3. On the one hand, the smallest action costs for $CO_{2,eq}$ LCA reduction in Finland belongs to scenario 1 based on the current battery technology and charging facilities with 371 €/ton $CO_{2,eq}$. This figure will increase up to 1,250 for scenario 5 (with the battery capacities of 210-890 kWh).

On the other hand, the smallest action costs for $CO_{2,eq}$ LCA reduction in Switzerland belongs to scenario 1 based on the current battery technology and charging facilities. Surprisingly, the relevant action cost of $CO_{2,eq}$ LCA reduction in scenario 1 is -5 €/ton $CO_{2,eq}$. The negative action costs for $CO_{2,eq}$ LCA reduction means that the benefits is more than the costs. As a result, 5 €/ton $CO_{2,eq}$ will be saved in costs for BET option compared to CT one. However, the relevant figure will increase up to 528 €/ton $CO_{2,eq}$ for scenario 5 (with the battery capacities of 210-890 kWh).

What could be the best scenario packages, in terms of potential $CO_{2,eq}$ reduction and action costs for short and long-term horizons, of battery and charging infrastructures in BETs in Finland and Switzerland?

Based on the detailed discussion in Section 5.5, the best scenario package for the short and long-term horizons in Finland are scenario 2 and 4, respectively. For short-term horizon in Finland, the 77% tips (43% tkm) of the range needs can be best responded by access to the on-road fast-charging facilities with 150 kW power, the current battery capacity technology, and ERS in some routes. The relevant potential $CO_{2,eq}$ LCA reduction is 24% for scenario 2 which are accounted for 0.60 million tons $CO_{2,eq}$ per year. For long-term horizon in Finland, 94% trips (89% tkm) of the range needs can be best responded by access to the fast-charging facilities with 450 kW power and the battery capacity with the 50% increase. The relevant potential $CO_{2,eq}$ LCA reduction is 35% for scenario 4 which are accounted for 0.87 million tons $CO_{2,eq}$ per year. While, in Switzerland, for both short and long-term horizons, 89% trips (84% tkm) can be best responded by access to the on-road fast-charging facilities with 50-120 kW power and the current battery capacity technology. The relevant potential $CO_{2,eq}$ LCA reduction is 56% for scenario 1 which is accounted for 0.93 million tons $CO_{2,eq}$ per year.

It must be noticed that, if the given numbers aimed to be used for the future planning, the future growth for freight demand and the market entrance situation for the BET technology adoption must be considered.

6.2 Further discussions

By comparing the cost and emission results of this thesis to the research studies conducted by Mareev et al. (2018) and Huismans (2018), it is confirmed that battery cost and fast charging infrastructure costs has a major impact on the economic viability of road freight electrification. Huismans (2018) concluded that if the cost of the battery reduces to less than 200 €/kWh and the battery performance increases from 3,000 cycles to 6,000 cycles (equivalent for 4 years battery lifetime), the electrification of heavy-duty trucks (with GVW of 40 tons) will turn into an economically viable option in Netherland. Mareev et al. (2018) also concluded that the same results can be achieved in Germany, if the battery pack cost of 145 €/kWh and 7 years battery lifetime (with battery performance of 7,400 cycles or the battery life cycle mileage variation of 895,800-939,600 km) are assumed.

However, this thesis considered more practical routing assignment based on the available travel survey data and a wider range of BETs (with GVW of more than 3.5 tons). The results of this thesis show that the battery pack cost of 160 €/kWh for battery pack capacities of 190-330 kWh, and 4 years battery lifetime (with battery life cycle mileage variation of 248,208-257,080 km) can turn the BETs to an economically viable option compared to CTs in Switzerland.

The results also show that in Finland, according to the sensitivity analysis of TCO for the current battery technology and charging facilities, the relevant price of battery pack capacities of 190-330 kWh, and 4 years battery lifetime (with battery life cycle mileage variation of 151,480-301,388 km) should be around 86 €/kWh (with 46% reduction in battery costs). However, the relevant potential of road freight electrification based on the current battery technology would not cover the trips by the trucks with GVW of more than 40 tons. Therefore, even though the larger battery packs with the longer battery lifetime can be applied to fulfil the range needs in Finland, the TCO of BET is still higher than the CT option in Finland.

According to the Berger (2016), the $CO_{2,eq}$ abatement costs for using long-range BET, with 65 kWh capacity, varied from 475 to750 €/ton. However, the different scenario packages for road freight electrification by BETs led to variation of the $CO_{2,eq}$ abatement costs from 106 to 310 €/ton and from -3 to 255 €/ton in Finland and Switzerland, respectively. Firstly, the $CO_{2,eq}$ abatement costs potential estimated in this thesis, even by the assumption of bigger battery capacities, are improved compared to the results of Berger (2016). Secondly, according to Berger (2016), there are other cost-efficient vehicle types which can lead to the high GHG emission abatement cost potential.

Accordingly, the biofuel alternatives for gasoline (E10 to E20), as well as the gasoline and diesel hybrid technologies, can be the most cost-efficient alternative solutions for GHG reduction with the $CO_{2,eq}$ abatement costs potential vary from 10 to 200 €/ton. Even though Berger (2016) clearly stated that the biofuels, as well as gasoline and diesel hybrid technology, are the more cost-efficient options compared to the BEVs, the cost and emission measures must be checked carefully for the same payload capacity truck classifications.

Similarly, the cost-efficiency of the other complementary solutions like battery-swapping and range-extenders technologies can be analysed based on the same payload capacity truck classifications. However, regarding the scope and limits of this thesis, further discussion about such alternative solutions are off the topic.

Interestingly, the results of this thesis can be applied for different purposes. First, the results can be helpful for the different feasibility study projects in sustainable development in freight transport contexts. Second, the results can be helpful for short and long-term resource planning projects. For example, the electricity grid requirements in different scenario packages can be specified based on the fast charging, and home charging facilities for different regions via geographic information systems (GIS) and planning tools. Finally, from the academic perspective, this thesis provides a deep spatial analysis of the $CO_{2,eq}$ LCA and TCO for the road freight transport with GVW greater than 3.5 tons in Finland and Switzerland. Therefore, the methodology and results can promote future sustainability developments and discussions on road freight transport in Europe.

Regarding the above discussions, two main research topics are suggested to be conducted in the future to discuss the GHG reduction potential and the action costs of decarbonizing solutions in road freight transport. Firstly, using battery-swapping and range-extender technologies should be evaluated in practical details of TCO and $CO_{2,eq}$ LCA. Secondly, the impact of the cleaner or greener engine technology or/and fuels such as the biofuel engine solutions must be evaluated for different payload capacity classifications.

7. CONCLUSIONS

In today's life, battery electric vehicles (BEVs) can be an effective option to tackle the greenhouse gas (GHG) emission issues concerned with the road transport sectors. Freight transport has a large share of road transport GHG emissions. Regarding the policy strategies in Europe, different target and goals have been set for GHG reduction. Freight transport electrification is one of these targets and goals. However, many strategic planners are not sure about the real action costs and the potential of GHG reduction for different alternative solutions compared to the conventional diesel truck. The range anxiety has been one of the main issues with BEV's adoption in different weight classes. However, the range anxiety associated with medium and heavy-duty BEVs is intensified by battery capacity and fast charging limits.

This study was conducted to estimate the potential of electrifying road freight transport by implementing the battery electric trucks (BETs). For this purpose, regarding the available precious freight travel survey data in Finland and Switzerland in 2016, which previously used by Liimatainen et al. (2019), the scope of the research was set in these geographical boundaries. In terms of methodology, a three-step framework has been applied to estimate and analyse the electrifying potential of road freight transport in Finland and Switzerland.

The framework consists of three stages of data preparation, electrification analysis, and emission-cost analysis. The data preparation and electrification analysis were mainly specified based on the battery electric vehicle potential (BEVPO) model requirement settings. BEVPO model was developed by Melliger et al. (2018) to provide an accurate estimation of the electrifying potential of BEV. However, the application of BEVPO model for the medium and heavy-duty truck electrification had few challenges such as the wider range of energy consumptions and the battery capacity limits for long-haul trips. Figure 26 represents the suggested framework and the results in one shot.

The important findings of this thesis are in two-fold. Firstly, as Liimatainen et al. (2019) concluded, Finland has less potential for electrification potential by using the current technology of battery and fast charging compared to Switzerland. However, the results from the BEVPO model led to the better electrification potential with 20% and 70% growth which are accounted for 10% and 84% of all trips coverage based on tkm measure in Finland and Switzerland, respectively. The differences in the electrification potential in Finland and Switzerland might result from the different road network size and shape, fast charging service area coverage, cargo weight, capacity limits of trucks (76 vs. 40 tons GVW), and freight travel origin-destination (O-D) data.

Secondly, the emission-cost analysis was extended by using the LCA reduction potential and action costs measures in both countries. The results showed that the current technology scenario in Switzerland is a viable option for short and long-term horizons with the potential of $CO_{2,eq}$ LCA reduction by 56% and the action costs of -5 €/ton, which is accounted for 0.93 million tons $CO_{2,eq}$ per year. The negative action costs for $CO_{2,eq}$ LCA reduction means that the benefits is more than the costs. As a result, 5 €/ton $CO_{2,eq}$ LCA reduction will be saved in the relevant electrification scenario. While, in Finland, the current technology with the complementary ERS (overhead line) in the 2,384 km of the main road networks could be the best option for the short-term horizon with the potential of $CO_{2,eq}$ LCA reduction by 24% and the action costs of 550 €/ton, which is accounted for 0.60 million tons CO2 per year. Scenario 4 was selected as the best option for the long-term horizon in Finland with the assumption of 50% increase in the battery capacity of the currently available EVs model as well as access to the fast charging facilities with the 450-kW power. Scenario 4 in Finland led to the potential of $CO_{2,eq}$ LCA reduction by 35% and the action costs of 522 €/ton, which is accounted for 0.87 million tons CO2 per year.

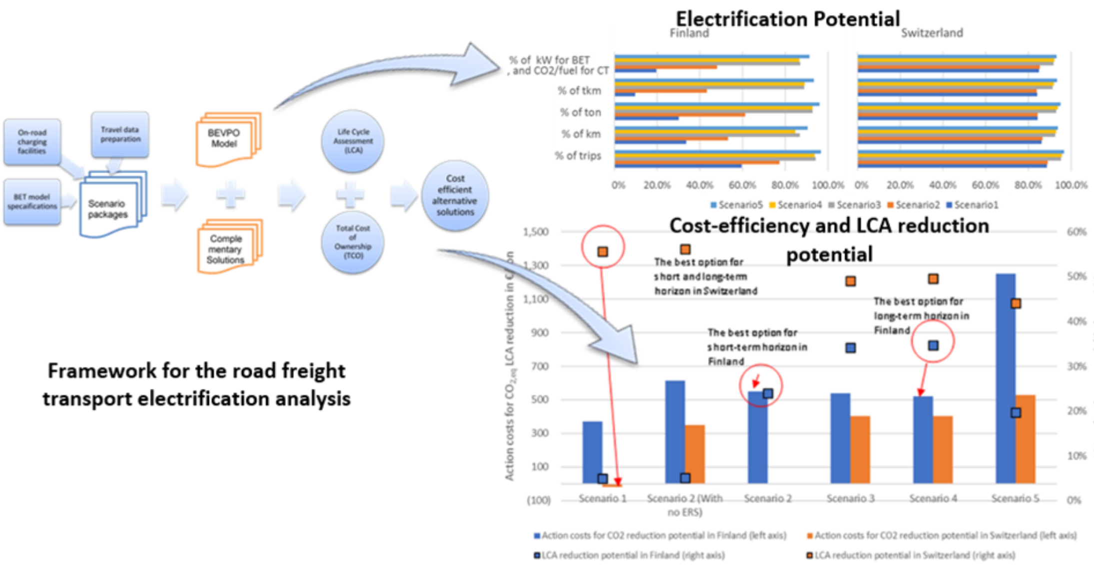


Figure 26. *Thesis' framework and the results.*

Despite the interesting results achieved from this study, there are some limitations. First, the high uncertainty range for the emission-cost estimation and analysis can be reduced by the future empirical researches for different truck weight classes. Second, considering the actual payloads in the simulation procedure of the BEVPO model may lead to more accurate results. Third, the other cost-efficient decarbonising alternative technologies such as biofuel and hybrid engines can be analysed in the road freight transport based on the same weight truck classes and freight travel data. Finally, the other complementary solutions such as battery-swapping and range-extended technologies can be analysed by future empirical research for different truck weight classes.

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APPENDIX A: BATTERY ELECTRIC TRUCK (BET) MODELS

Manufacturer	Name vehicle	Energy consumption (kWh/km)	Motor [kW]	Battery [kWh]	Range[km]	Weight loaded (GVW) [tons]	Weight empty (Kerb weight) [tons]	Net Weight payload	Charging time [h]	Charging power (kW)	Charge current (A)	Source
EMOSS	EMS 712		120	120	160	12	8	4	…	22/44	32/64	http://www.emoss.nl/wp-content/uploads/brochure_emoss_2016_web.pdf
EMOSS	EMS 1008		150	80	100	15	10	5	…	22/44	32/64	http://www.emoss.nl/wp-content/uploads/brochure_emoss_2016_web.pdf
EMOSS	EMS 1212		150	120	150	19	12	7	…	22/44	32/64	http://www.emoss.nl/wp-content/uploads/brochure_emoss_2016_web.pdf
EMOSS	EMS 1220		150	200	250	17	12	5	…	22/44	32/64	http://www.emoss.nl/wp-content/uploads/brochure_emoss_2016_web.pdf
EMOSS	EMS 1612	0.8	150	120	125	26	16	10	…	22/44	32/64	http://www.emoss.nl/wp-content/uploads/brochure_emoss_2016_web.pdf
EMOSS	EMS 1620	0.8	150	200	210	25	16	9	…	22/44	32/64	http://www.emoss.nl/wp-content/uploads/brochure_emoss_2016_web.pdf
EMOSS	EMS 1820	0.9	230	200	190	29	18	11	…	22/44	32/64	http://www.emoss.nl/wp-content/uploads/brochure_emoss_2016_web.pdf
EMOSS	EMS 1824	0.9	230	240	230	28	18	10	…	22/44	32/64	http://www.emoss.nl/wp-content/up-

												loads/bro-chure_emoss_2016_web.pdf
Hytruck	C12E		150	120-200	170-220	12	...		4.4	22/44	32	http://www.hytruck.nl/modellen/C12E/
Hytruck	C16E		235	120-200	160-260	16	...		4.4	22/44	32	http://www.hytruck.nl/modellen/c16e/
Hytruck	C18E		300	120-200	150-250	19	...		4.4	22/44	32	http://www.hytruck.nl/c18e/
Tesla	Semi 400		...	760	475	36	...		...	...	...	https://www.tesla.com/nl_NL/semi...redi-rect=no
Tesla	Semi 800		...	1520	800	36	...		...	...	...	https://www.tesla.com/nl_NL/semi...redi-rect=no
Balqon	MX30 Class 8	1.4	240	320	201	40	15	25	4-6	40-60		https://en-ergy.gov/sites/prod/files/2014/03/f13/vss115_choe_2013_o.pdf
Nautilus	XRE20		240	140	94	40	-		1.4			https://www.au-toblog.com/2010/01/20/balqon-adds-extra-heavy-dutyhauler-to-range/?guccounter=1
TransPower	ElecTruck		300	269	113	-	-		4			https://en-ergy.gov/sites/prod/files/2014/03/f13/vss115_choe_2013_o.pdf
US Hybrid	eTruck (Class-8 Truck)		320	160-240 (Li-Ion)	128	29.4	-		3			https://en-ergy.gov/sites/prod/files/2014/03/f13/vss115_choe_2013_o.pdf
GINAF	E2112		280	120-240	150/225/295	12	8-10	2.6-6	1.5-4.5	22-66		http://www.ginaf.nl/fileadmin/in-houd/Trucks/folder/E-Serie.pdf
GINAF	E2114		280	120-240	130-260	13.5	8-10	4-6	1.5-4.5	22-66		http://www.ginaf.nl/fileadmin/in-houd/Trucks/folder/E-Serie.pdf
GINAF	E2115		280	120-240	130-260	15	8-10	5.5-7	1.5-4.5	22-66		http://www.ginaf.nl/fileadmin/in-houd/Trucks/folder/E-Serie.pdf
GINAF	E2119		280	120-240	110-220	19	8-10	8-9.2	1.5-4.5	22-66		http://www.ginaf.nl/fileadmin/in-houd/Trucks/folder/E-Serie.pdf
GINAF	E2121		280	120-240	100-200	20.5	10-12	9.4-10.7	1.5-4.5	22-66		http://www.ginaf.nl/fileadmin/in-houd/Trucks/folder/E-Serie.pdf

GINAF	E3126		280	180	75	26	-		1.5-4.5			http://www.ginaf.nl/fileadmin/in-houd/Trucks/folder/E-Serie.pdf
GINAF	E3126		280	120	75	26	-		1.5-4.5			http://www.ginaf.nl/fileadmin/in-houd/Trucks/folder/E-Serie.pdf
Motiv	Epic E-450 chassis		150	127	161	6.6			2.5-8	17		http://www.mo-tivps.com/mo-tivps/portfolio-items/epic-e-450-box-truck/
Motiv	Epic F-59 chassis		250	127	145	10	6	4	2.5-8	17		http://www.mo-tivps.com/mo-tivps/portfolio-items/epicf59-allelec-tric-stepvan/
Motiv	Refuse truck		250	212	129	30	21		6			https://ti-nyurl.com/yd94htbx
Orange EV	Terminal truck		-	-	-	37?	-		2			https://orang-eev.com/t-series-new/
BYD	Class 8 day cab	1.8	360	435	200-270	47.6	11.5	36	1.5-3	300 kw		https://en.byd.com/truck/#models
BYD	Class 6-cab chas-sis		250	221	200	11.8	4.7		1.5-4.5	150 kw		https://en.byd.com/truck/#models
BYD	T9	1.1	180	188	148	54	11	43	2.5			http://en.byd.com/usa/wp-content/up-loads/2017/06/t9-fi-nal.pdf
Wright-speed	Repower Kit		-	-	-	-	-		-			https://www.trucks.com/2017/02/21/tesla-electric-garbage-truck-swrightspeed/
E-Force One	E44		350	310	300	-	9		6			https://eforce.ch/up-loads/1/1/7/1/117106312/e44_fact_sheet_e.pdf
Renault & Group Delanchy	D13 Elec-trique						13		-			https://cleantech-nica.com/2017/12/16/electric-semi-trucks-heavy-dutytrucks-avail-able-models-planned-models/
Cummins	AEOS		-	145	161	22	8		1			https://en.wikipe-dia.org/wiki/Cum-mins_Aeos
MAN	eTruck		250		200	18-26	-					https://www.truck.man.eu/de/en/eTruck.html

Thor	ET-One		-	-	483	36	-		1.5			https://www.thecarconnection.com/news/1114319_thor-trucks-arrives-asthe-latest-electric-semi-competitor
VDL groep	DAF CF Electric	1.4	210	170	100	40	10	30	1.5			http://www.daf.com/nl-nl/news-and-media/articles/global/2018/q2/16-05-2018-daf-partners-with-vdl-groep-for-fully-electric-cf-truck
Daimler	eCascadia		544	550	400	27			1.5			https://newatlas.com/daimler-trucks-freightliner-electrics/54946/
Daimler	eM2 106		358	325	370				1			https://newatlas.com/daimler-trucks-freightliner-electrics/54946/
Daimler	Mercedes-Benz		250	212	200	26						https://www.daimler.com/products/trucks/mercedes-benz/world-premieremercedes-benz-electric-truck.html
Daimler	E-Fuso One		-	300	350	34	23		-			https://www.daimler.com/innovation/case/electric/efuso-2.html