MASTER'S THESIS

# ENVIRONMENTAL AND ECONOMIC SUSTAINABILITY OF ZERO-EMISSION BUS TRANSPORT

Orkide Nur Kara

INDUSTRIAL ENGINEERING & MANAGEMENT
SPECIALIZATION: PRODUCTION & LOGISTIC MANAGEMENT

FACULTY OF BEHAVIOURAL, MANAGEMENT AND SOCIAL SCIENCES
DEPARTMENT OF INDUSTRIAL ENGINEERING AND BUSINESS INFORMATION SYSTEMS

14-06-2019

UNIVERSITY OF TWENTE.

| | |
|---|---|
| Document | Master's thesis |
| Document title | Environmental and economic sustainability of zero-emission bus transport |
| Date | 14-06-2019 |
| Author: | Orkide Nur Kara<br>o.n.kara@alumnus.utwente.nl |
| Master's program | Industrial Engineering & Management<br>Specialization: Production & Logistic Management |
| Graduation committee<br>University of Twente | Dr. D.M. Yazan<br>Faculty of Behavioral Management and Social Sciences |
| | Dr. L. Fraccascia<br>Faculty of Behavioral Management and Social Sciences |
| Company X | Ir. J. Kornet<br>Head of Industrial Automatization and Innovation |
| | B.N.J. Liefkens MSc<br>Project engineer |
| | E. Teunissen MSc<br>Project engineer |

UNIVERSITY
OF TWENTE.

# Management summary

This study has been conducted at Company X as an MSc thesis for the study Industrial Engineering & Management. Company X is an engineering and consultancy firm that provides consultancy services to government, companies and other institutions in the fields of infrastructure, water, construction, and environment. The company has lately been involved in a lot of research about the feasibility of charging strategies for the electric public bus transport in particular regions. In recent years, zero-emission public bus transport has been a hot topic in the Netherlands, as more and more electrical fleets are deployed or planned in various cities and regions.

The electrification of public bus transport can be carried out utilizing different technological solutions, like trolley, battery or fuel cell buses. The available zero-emission technologies are broadly reliable, but in particular, there are still uncertainties about different charging scenarios. Currently, feasibility studies are being conducted in which various charging scenarios are being analyzed before really scaling up. Majority of these studies focus on the operational phase of bus transportation, while other relevant processes in the supply chain of bus transportation are usually not considered. In particular, the impact of the batteries in the supply chain of bus transportation is not given (sufficient) attention.

In this research, the intention is to understand the sustainability of the supply chain of bus transportation by focusing on the impact of batteries. Through a case study, this study aims to analyze the environmental and economic sustainability of the battery bus transportation based on three charging strategies: overnight charging, opportunity charging and the combination of overnight and opportunity charging. Second, this research aims to provide a practical contribution to the stakeholders to better design the zero-emission bus transportation. In order to reach these goals, the research question has been identified as:

*What are the net environmental and economic costs/benefits of battery buses with overnight charging, opportunity charging and the combination of both charging strategies?*

Enterprise input-output modeling is being adopted to assess the environmental and economic sustainability of the supply chain of battery bus transportation in the case of bus line Y. The impact of the implementation of the charging strategies on the sustainability of the supply chain is being quantified using scenario analysis. First, desk research is being carried out to gain a broad understanding of the field. Thereafter, the processes in the supply chain of the battery bus transportation are being identified and data with respect to these processes is being collected. Data is being collected through interviews with experts from the company and from literature and the ecoinvent database. After data collection, the data is being converted into useful inputs to EIO. The output of EIO modeling consists of two models: the physical and monetary EIO model. First, we adopt a physical input-output model to display the material, energy and $CO_2$ flows in the supply chain of bus transportation and then integrate it into a monetary input-output model via cost/price vectors. For each scenario, we compute the economic and environmental performance indicators and discuss the results comparatively. For that purpose, $CO_2$ emission serves as the environmental sustainability indicator while total costs serve as the economic sustainability indicator. The results from EIO modeling is being used to answer the research question and draw conclusions with respect to the purpose of the thesis.

The physical input-output tables show that scenario III: opportunity charging has the lowest primary input consumption and $CO_2$ generation with a yearly emission of 164,314 kg. This is due to the smaller batteries in the scenario, which require less amount of material during battery production

and also consume less electricity during bus operation. In all scenarios, it can be observed that aluminium is the most important material input. Furthermore, a small difference can be observed in the required workforce in the scenarios. The monetary input-output tables show that scenario III has the lowest environmental costs with € 12,324 per year and the lowest total costs with € 318,608 per year. Moreover, the results show that on average the highest costs per year are made for the workforce (63% of the total costs), followed by electricity costs (21%) and investment costs (10%).

It can be concluded that scenario III is the most environmentally and economically sustainable charging scenario in the case of bus line Y. The outcome of the enterprise input-output modeling shows that the majority of the $CO_2$ emission in the supply chain of battery bus transportation originates from fuel-related emissions, and not from battery-related emissions. However, the impact of battery size is significant. The benefits of small battery capacity can be observed in the results, i.e. less material and electricity use in both production and operation processes, resulting in less $CO_2$ emission. Hence, a reduction of the weight of the battery and the related electricity consumption will drastically reduce the impacts linked to electricity generation. With respect to charging strategies, it can be concluded that the use of smaller SOC windows prolongs the battery life and is only useful with smaller batteries. Finally, a significant incentive to create a local production model can be observed. The current business model can be extended to a case where an open-loop supply chain is created. In such a model, aluminium in the batteries can be recycled and used in the production of other bus components or sold to local parties outside the supply chain.

In a future analysis, it is important to include the end of life treatment of the batteries. There are two interesting scenarios to consider for in the future: 1) recycling of battery key raw materials (aluminium) and 2) reusing the battery cells in a stationary storage system to charge the buses. For now, there might not be a business case for recycling EV batteries. Under current circumstances of absence of substantial waste streams combined with low battery prices and high recycling costs, the infrastructure targeting bus batteries should still be adapted to the expected increase of batteries flows and to recover specific materials. This research can be extended by including the remaining actors in the supply chain, other battery chemistries and battery key raw materials that provide a significant incentive for recycling. Furthermore, this study can be expanded to the entire bus network taking especially the influence of vehicle scheduling on the system design into account.

# Preface

This MSc thesis has been written to acquire my master's degree in Industrial Engineering & Management. The report is the result of my six-month internship at Company X, where I conducted my graduation project. Many people accompanied me in this process. That is why I would like to take this opportunity to thank them.

First of all, I would like to thank my first supervisor from the university, Devrim Yazan, for his personal involvement and excellent guidance and support throughout the process. I would also like to thank my second supervisor, Luca Fraccascia, who has lately been involved in my research, though provided me with very useful feedback.

Moreover, I want to thank my main external supervisor Johan Kornet for giving me the opportunity to write my MSc thesis about such an interesting and important topic. His critical feedback and valuable insight supported me in achieving this great result. I would like to thank my second and third external supervisors, Bjorn Liefkens and Erwin Teunissen, for the useful discussions and giving me good directions in my research. I would also like to thank other employees who were always willing to make time for my questions and helped me this way in the collection of the necessary information. In addition, I would like to thank my friends at Company X, for their support and the pleasant lunches and coffee breaks.

Finally, I want to thank my family for the continuous support and motivation during my entire master's program. I would, especially, like to thank my mom, whose love and support I have always felt.

Orkide Nur Kara

Enschede, June 2019

# List of Abbreviations

| | |
|---|---|
| BEV | Battery Electric Vehicle |
| CE | Circular Economy |
| CRM | Critical Raw Material |
| DOD | Depth Of Discharge |
| EEA | European Environment Agency |
| EIO | Enterprise Input-output |
| EOL | End of Life |
| ESS | Energy Storage System |
| EV | Electric Vehicle |
| FCEV | Fuel Cell Electric Vehicle |
| HVAC | Heating, Ventilation and Air Conditioning |
| HEV | Hybrid Electric Vehicles |
| LIB | Lithium Ion Battery |
| SOC | State of Charge |
| SSC | Sustainable Supply Chain |
| TBL | Triple Bottom Line |
| TCO | Total Cost of Ownership |
| TTW | Tank to Wheel |
| WTT | Well To Tank |
| ZEB | Zero-Emission Bus |

# List of Definitions

| | |
|---|---|
| Battery electric vehicles | are powered solely by an electric motor, using electricity stored in an on-board battery. |
| Circular economy | is an alternative to the traditional linear economy, which focuses on make, use and dispose. The emphasis of the circular economy is to keep the value of materials and products as high as possible for as long as possible. |
| Critical Raw Material | can be defined as a raw material that is both of high economic importance for the European Union and vulnerable to supply disruptions. |
| Cycle life | refers to the number of charge-discharge cycles a battery can deliver before capacity drops below a certain threshold percentage of its original capacity. |
| Depth of Discharge | is the percentage of battery capacity that has been discharged expressed as a percentage of maximum capacity. |
| Energy density | is a measure of how much electrical energy can be stored per unit volume or mass of the battery. This measure is relevant to vehicle range, as batteries with a higher energy density are typically able to power a vehicle for longer distances. |
| Fuel cell electric vehicles | are entirely propelled by electricity. The electric energy is provided by a fuel cell 'stack' that uses hydrogen from an on-board tank combined with oxygen from the air. |
| Pantograph | is used for charging of electric buses that makes physical contact with a charging point to conduct electrical current (conduction) to the batteries of the buses. |
| Peak shaving | describes when a facility uses a local energy storage system to compensate for the facility's large energy consumption during peak hours of the day. Peak shaving is similar to load leveling, but may be for the purpose of reducing peak demand rather than for economy of operation. |
| Power density | a measure of power per unit volume, i.e. how fast a battery can deliver or take on charge. This measure is relevant for driving performance, i.e. acceleration and driving speed, and charging times. |
| Recycling | refers to reuse of material from used products and components, whereby the used products are disassembled to material level and the separated parts are reused in the production of new parts. |
| State of Charge | is a representation of the percentage of the current capacity in relation to the maximum battery capacity. The SOC |

| | |
|---|---|
| | decreases during the bus cycle due to energy consumption, while it increases during the charging process. |
| Total Cost of Ownership | is an estimate that attempts to find all lifecycle costs that follow from asset ownership. It includes the purchase price of the asset and the direct and indirect costs of operation. |
| Tank-to-Wheel | refers to the combustion in the engine, i.e. the direct impacts of driving the vehicle. |
| Well-To-Tank | refers to the emissions that are created during the production of energy, e.g. electricity or hydrogen. |

# Table of Contents

Management summary ..... II

Preface ..... IV

List of Abbreviations ..... V

List of Definitions ..... VI

1. Introduction ..... 1

1.1. Context ..... 1

1.2. Dutch action towards a zero-emission bus fleet: ZEB transport ..... 1

1.2.1. The objectives of sustainable public transport ..... 1

1.2.2. Current situation ..... 2

1.2.3. Zero-emission buses ..... 3

1.2.4. Transition paths ..... 3

1.2.5. Stakeholders in the supply chain ..... 4

1.3. Problem description ..... 4

1.4. Research question and sub questions ..... 4

1.5. Limitations ..... 5

1.6. Structure of the report ..... 5

2. Theoretical framework ..... 6

2.1. Sustainability ..... 6

2.1.1. Triple Bottom Line (TBL) perspective ..... 6

2.1.2. Sustainable supply chains (SSC) ..... 7

2.1.3. Supply chains in circular economy ..... 8

2.2. Enterprise input-output (EIO) modeling ..... 9

2.2.1. Introduction ..... 9

2.2.2. EIO models for supply chains ..... 11

2.2.3. Summary of EIO studies ..... 12

3. Literature research ..... 13

3.1. Bus and charge technologies ..... 13

3.1.1. Battery buses ..... 13

3.1.2. Electric charging techniques ..... 14

3.1.3. Factors affecting energy consumption ..... 15

3.1.4. Environmental considerations ..... 16

3.1.5. Advantages and disadvantages of BEVs ..... 18

3.2. Batteries ..... 19

3.2.1. Lithium-ion batteries ..... 19

3.2.2. Battery chemistries ..... 20

3.2.3. Battery lifetime ... 21
3.2.4. End of life treatment of EV batteries ... 23
3.2.5. Second life: stationary storage ... 23
4. Methodology ... 25
4.1. Methodology ... 25
4.1.1. Method ... 25
4.1.2. Goal ... 25
4.1.3. Scope ... 25
4.1.4. Limitations ... 26
4.2. Presentation of the case ... 26
4.2.1. Bus line Y – Station Z ... 27
4.2.2. Actors in the supply chain ... 27
4.2.3. Scenario I: Overnight charging ... 27
4.2.4. Scenario II: Overnight and opportunity charging ... 28
4.2.5. Scenario III: Opportunity charging ... 29
5. Assumptions ... 30
5.1. General assumptions ... 30
5.1.1. Battery composition ... 30
5.1.2. Battery life ... 30
5.1.3. Energy consumption ... 31
5.1.4. Charging strategy ... 32
5.2. Assumptions per scenario ... 33
5.2.1. Scenario I: Overnight charging ... 33
5.2.2. Scenario II: Overnight and opportunity charging ... 34
5.2.3. Scenario III: Opportunity charging ... 36
6. Results and discussion ... 38
6.1. Environmental sustainability ... 38
6.2. Economic sustainability ... 41
7. Conclusion & future research ... 45
7.1. Conclusion ... 45
7.2. Future research ... 46
References ... 48
Appendix A: Zero-emission buses in the Netherlands ... 53
Appendix B: Stakeholders in the supply chain ... 54
CONFIDENTIAL Appendix C: Bus schedules ... 55
Appendix D: Expected cycle life of $LiFePO_4$ battery cells ... 56

CONFIDENTIAL Appendix E: Assumptions in the scenarios .................................................................. 58

# 1. Introduction

*In this chapter a brief background and problematization for the phenomena under investigation is presented, followed by the research purpose and questions this thesis is going to address. Finally, the limitations of the research is discussed and the structure of the report is presented.*

## 1.1. Context

Worldwide, sustainable mobility is given a lot of attention to contribute simultaneously to clean air, a better climate, and green growth. Efforts to increase the sustainability of mobility are often focused on limiting energy demand, using sustainable energy and, if necessary, using fossil fuels as efficiently and cleanly as possible. On 6 September 2013, more than forty organizations, including the government, employers, trade unions, nature and environmental organizations, other civil society organizations and financial institutions, joined the National Energy Agreement for sustainable growth. The core of the agreement is broad-based agreements on energy saving, clean technology, and climate policy. Implementation of the agreements must result in affordable and clean energy supply, employment and opportunities for the Netherlands in the clean technology markets. Within the climate agreement, the following targets have been agreed for the transportation sector: 25 Mton $CO_2$ in 2030 and 12.2 Mton $CO_2$ in 2050 (Rijksoverheid, 2019). The current emissions of this sector are around 38 Mton $CO_2$ equivalents per year (Ministerie van Infrastructuur en Milieu, 2019). One of the short-term measures concerns the perspective that 'a model specification and agreements with concession providers on climate objectives' will make public transport more sustainable. One of the themes for which preconditions and performance requirements are formulated in tendering is sustainability. The Dutch public transport bus fleet only comprises around 5,000 vehicles on a total fleet of around 8 million. The bus fleet is, still, responsible for 2% (0.5 million tonnes) of the $CO_2$ emissions from road traffic (Interprovinciaal Overleg, 2015) and on certain urban routes for a relatively large part of the local exceedances of air quality standards (particulate matter and $NO_x$). Within the framework of the National Energy Agreement, the Vision and the Sustainable Fuel Mix Action Agenda were developed. In this process, the transition paths were set out under the leadership of the Ministry of Infrastructure and the Environment, by all relevant stakeholders in the field of sustainable mobility, to make various modalities more sustainable in the period 2030-2050. The key message is that the Netherlands is committed to road transport with electric vehicles (EV) for segments for which electric driving is promising. Electric driving is combined with sustainable biofuels and renewable gas as a bridging option and as a long-term solution for heavy transport. Both tracks are supported by a maximum commitment to efficiency measures. In the framework of the National Energy Agreement and with ever-increasing political, administrative and social pressure, the urgency and the importance of ambitiously tackling sustainability are high in the coming periods. The Netherlands already led the way with the first zero-emission buses (ZEB) in structural service (Schiermonnikoog, 2013), with induction (Utrecht and 's-Hertogenbosch), with large numbers (Eindhoven and Schiphol area), with fast charging solutions (Heliox), with its ZE bus industry (VDL), its national Green Deal targets for public transport buses and recently also with the first ZE buses intended for regional transport, namely Rnetlijn 316 from Amsterdam to Edam/Volendam.

## 1.2. Dutch action towards a zero-emission bus fleet: ZEB transport

### 1.2.1. The objectives of sustainable public transport

A Green Deal Zero-Emission bus transport was signed in October 2012 between the Dutch Ministry of Infrastructure and Water Management, the Province of Noord-Brabant and the Zero-Emission Bus Transport Foundation with the aim of supporting local authorities and market parties in making investment decisions about the use and the energy supply of ZEB equipment and the charging and refueling infrastructure. On 15 April 2016, the Dutch public transport authorities and the Ministry of

Infrastructure and the Environment signed the 'Zero-Emission Regional Public Transport Administration Agreement by Bus'. In the Administrative Agreement it has been agreed that:

1. Regional bus transport is completely emission-free at the exhaust by 2030, or as soon as possible.
2. From 2025 all new incoming buses will be emission-free at the exhaust.
3. New buses in 2025 use 100% renewable energy or fuel, which will be generated regionally as much as possible with a view to economic development.
4. Public transport concessions have the most favorable score on well-to-wheel $CO_2$ emissions per passenger kilometer.

### 1.2.2. Current situation

The transport authorities work on the basis of a joint intention, the zero-emission bus management agreement, on a transition to zero emissions that should lead to a 100% implementation in 2030, and the intermediate milestone of 2025 as the date after which no more diesel and natural gas buses can be purchased. In the zero-emission bus transport management agreement, it has been agreed that by 2030 all buses must be emission-free at the exhaust and must run on green power (or hydrogen). Currently, electrical fleets are deployed or planned in various cities and regions. Appendix A gives an overview of the regions in which the zero-emission buses are introduced in the Netherlands. In the spring of 2018, 5,147 public transport buses were operating in the Netherlands of which 291 were electric buses (CROW, 2018), which is 5.7% of the bus fleet. The top three areas with the highest number of electric buses are Amstelland-Meerlanden (AML), Zuidoost Brabant and the concession Arnhem Nijmegen, who have 100, 45 and 43 vehicles driving in the regions, respectively (Dragt, 2018). The most important sustainability is currently taking place in the new concessions Bus Transport Almere, Amstelland-Meerlanden and Haarlem/IJmond.

The number of zero-emission buses has more than doubled in 2018. At the end of 2017, the stand was 162 (including the natural gas buses in Arnhem), but at the end of December 2018 more than 350 zero-emission buses were operating in the Netherlands (CROW, 2019). This means that currently, 7% of the total public transport fleet does not cause emissions. At the end of 2018, more than 350 zero-emission buses were operating in the Netherlands, of which:

- the majority of the zero-emission buses use intermediate fast-charging in combination with slow-charging at night;
- a relatively large part of the buses only charges at night;
- a smaller part uses natural gas buses and intends to experiment with battery trolley buses;
- and eleven buses fill up with hydrogen.

Concession holders are currently still between pilot and scaling-up phase. In the period up to 2020, validation projects will be taking place with electric and hydrogen buses per project in multiple concessions. Certain routes or line bundles can then be made emission-free. In recent years, mainly technical pilots have been carried out in which knowledge about the interaction between bus and charging system has been gained. The techniques that are available are broadly reliable, but in particular, there are still uncertainties about different charging scenarios. Currently, various scenarios are analyzed before really scaling up. Charging is an important subject, as the lifetime of the battery greatly depends on it. The implementation of the charging infrastructure requires customization and the chosen charging technique is highly dependent on the local situation. Opportunity charging has been the most developed and manifested technology in recent years and is also the technique on which most of the buses are now (being) prepared in the Netherlands. This applies in particular to large-scale concession AML, where currently 100 buses are driving. Most of the concessions that already introduced electric buses into daily operation make use of charging via a plug and/or a pantograph. Overnight, the buses are charged at the depot by means of a plug, while during the day a pantograph is used for charging. A pantograph connects the bus to a charging point. The charging point, which is the physical part of the bus station, conducts the electrical energy to the batteries of the bus. A pantograph can be mounted on the roof of the bus and raised during charging ('pantograph up') or mounted on the charging pole and lowered to the contact rails on the roof of the bus ('pantograph down') for charging. This last choice is seen by the OppCharge consortium as the future standard (Elaad, 2017). Market parties seem to have a clear preference for charging by means of a pantograph, because a direct connection can be made between bus and charging infrastructure so that there is hardly any loss of energy (APPM, 2019). Figure 1 schematically shows both implementations of a pantograph system. Furthermore, the storage of energy can make an important contribution to the realization of a smart grid. More and more grid operators are considering bi-directional grids, where energy can be absorbed from and can be returned into. A Smart Grid Center will be realized in the coming concession Midden-Overijssel and after validation possibly in other regions as well.

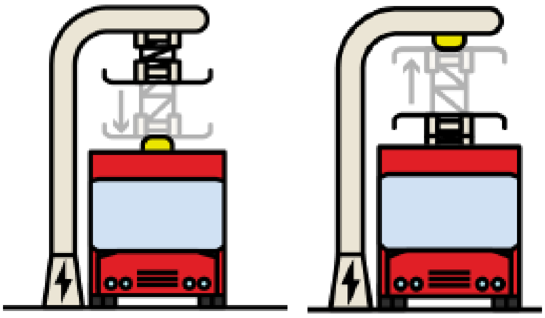


*Figure 1 Schematic representation of the pantograph system: option 1 - pantograph on a charging pole, option 2 - pantograph on a bus*

### 1.2.3. Zero-emission buses

The ZEB transport involves buses that have an electric powertrain instead of a combustion engine. There are currently six types of zero-emission buses: plug-in buses, opportunity charging buses, trolley buses, in-motion charging (IMC) buses, hydrogen buses and electric buses with hydrogen range extender. It applies to all buses that the 'tank-to-wheel' emissions should completely be zero. Furthermore, overall sustainability can only be reached if the electricity or hydrogen used has been produced sustainably. Electric hydrogen-based driving is more in an initial phase than driving with buses that get their electricity from batteries. The high costs, in addition to technical challenges for the storage and production of hydrogen, are currently a barrier to upscaling experiments. For the time being, the operating costs of hydrogen buses are much higher than for battery-electric buses (SER, 2019). Buses with battery technology can now be used at least cost-effectively. For the transportation service provider, the total costs over the entire concession term are the most important factor when choosing between different ZEB variants. A low total cost of ownership (TCO) is therefore a predictor of the technology that will be used. TCO includes all costs that are related with ownership, deployment and disposal of bus equipment. All in all, the hydrogen development is currently lagging behind from a cost and technological point of view, but is seen as a serious alternative.

### 1.2.4. Transition paths

Concessions usually run for eight years, so in current tenders ZE buses are not yet mandatory. Nevertheless, the Public Transport (OV) authorities want to speed up and want the providers to use a number of ZE buses on a voluntary basis. The year 2025 has been chosen as a common goal, but concession providers can anticipate this if it suits the tender calendar and natural moments of fleet replacement. According to many parties, electric bus transport in a city in 2020 is feasible, transition of a whole concession (urban and regional transport) to zero-emission is, however, possible in 2030 (Elaad, 2017). This must be possible in a maximum of two concession terms. The zero-emission operation of the first 20-25% of the number of buses is feasible, while the upscaling to approximately 75% of the buses is expected to be more difficult (APPM, 2019).

The parties agree that hydrogen is the most feasible option in the regional transport in the long term, on the understanding that the costs of a hydrogen bus and hydrogen should not be too high and that there is sufficient fuel infrastructure (APPM, 2019). Until this is the case, whereby no dates are mentioned by the parties, several transition paths are possible in the regions. Green gas, biofuels, and hybrid are the most common forms here, although green gas is seen as an interim solution, since it is not completely sustainable.

#### 1.2.5. Stakeholders in the supply chain

The switch to clean and affordable public bus transport requires cooperation between all parties in the chain. These are primarily public transport authorities, transport companies, municipalities and (grid) operators. But the collaboration also extends to manufacturers of buses, batteries and energy infrastructure and asset managers. The city and regional public transport are organized by fourteen public transport authorities (concession providers), namely the twelve provinces and the two transport regions. They outsource the public transport contract whereby the transport company (the final concession holder) is awarded an assignment for 8-10 years. In the current, mostly non-zero emission situation, the concession holder owns the bus and tank infrastructure, whereby refueling often takes place in the depot. In the situation of zero-emission, the dependence on the charging infrastructure (in the case of electric) or a filling point (in the case of hydrogen) is great. There can be several legal owners: the owners of buses can be transport companies or lease companies, but also concession providers. The owners of fuel filling points or electric charging points can be the transport companies, or real estate parties or municipalities that rent the depots. In the case of electric buses that make use of charging via the pantograph, there is also an owner of the required energy infrastructure. The dependence on the infrastructure and the investments that go with it, create essential questions about who should take which responsibility and how to deal with infrastructure and energy supply. The parties' views on who is responsible for the infrastructure differ greatly. However, there is an agreement that in the current situation of the start-up of zero-emission bus in (system)pilots, the transport company must have the ownership of infrastructure and bus. Appendix B presents the current course of concession granting and the stakeholders involved in this process.

### 1.3. Problem description

The current Dutch public bus transportation is reliable, familiar but noisy and not compliant with the Green Deal, while the Zero-Emission Bus transport is clean, silent, but work in progress. The transition to electric driving mainly contributes to the task of sustainability, but it is the challenge to also achieve financial gains compared to diesel bus transport. In this respect, many feasibility studies have been conducted to assess the suitability of charging strategies in the regions using a total cost of ownership approach. However, the majority of these studies focus on the operational phase, while other relevant processes in the supply chain of bus transportation, like the battery production, are usually not considered. The operation phase of the supply chain is emission-free, however, the processes prior and following might not. In this respect, the economic and environmental sustainability of the supply chain of the electric bus transport is not known.

### 1.4. Research question and sub questions

Understanding the sustainability of battery buses requires looking at its supply chain. This research aims to explore the environmental and economic sustainability of the supply chain of the battery bus transportation by focusing on the impact of the batteries. Second, it aims to provide a practical contribution to the stakeholders to better design the zero-emission bus transportation. In order to reach this aim, the research question has been identified as:

*What are the net environmental and economic costs/benefits of battery buses with overnight charging, opportunity charging and the combination of both charging strategies?*

Within this overarching goal, the thesis aims at answering the following sub questions:

1. What are the environmental and economic impacts generated by the electric battery bus transport in the charging scenarios?
    - Which actors are responsible for the majority of $CO_2$ emissions?
    - Which actors are responsible for the majority of costs?
    - Which scenario results in the most environmentally and economically sustainable charging strategy?
2. How can this analysis contribute to further decision support in the design of ZEB transport?

## 1.5. Limitations

There are a number of limitations that should be recognized. The first is the availability of data. Different stakeholders are involved in the making, the use and the disposal of the batteries, which disperse the required information over the entire supply chain and over time. Due to the fast-evolving battery market, batteries are available in different sizes and chemistries. Furthermore, the material composition and the battery lifetime are dependent on the battery type, battery manufacturer and product quality. This limitation leads to making assumptions about the material composition and lifetime of the batteries in the scenarios. The results of this research are intended to be used for support in the planning of the future bus service and to build up the knowledge base of bus transportation. The model covers the environmental and economic impacts resulting from the production and use of the batteries. Social sustainability is not being assessed in this thesis. In order to fully assess the sustainability of the electric buses and understand the dynamics of how these buses will work in a real setting, these aspects should also be investigated in future works.

## 1.6. Structure of the report

The thesis is structured into seven chapters. The following chapter includes a theoretical framework, presenting the context of this study and the theory behind the methodology applied. Chapter three presents the literature review of the technological characteristics and the environmental and economic benefits and drawbacks of the included bus and charging technologies. Chapter four presents the methodology and the case. Chapter five presents the collection of the necessary data to model the scenarios, including the assumptions made. The results are presented and discussed in chapter six. Finally, chapter seven focuses on answering the research question, drawing conclusions with respect to the purpose of this thesis and making suggestions for future research. The thesis is structured according to Figure 2.

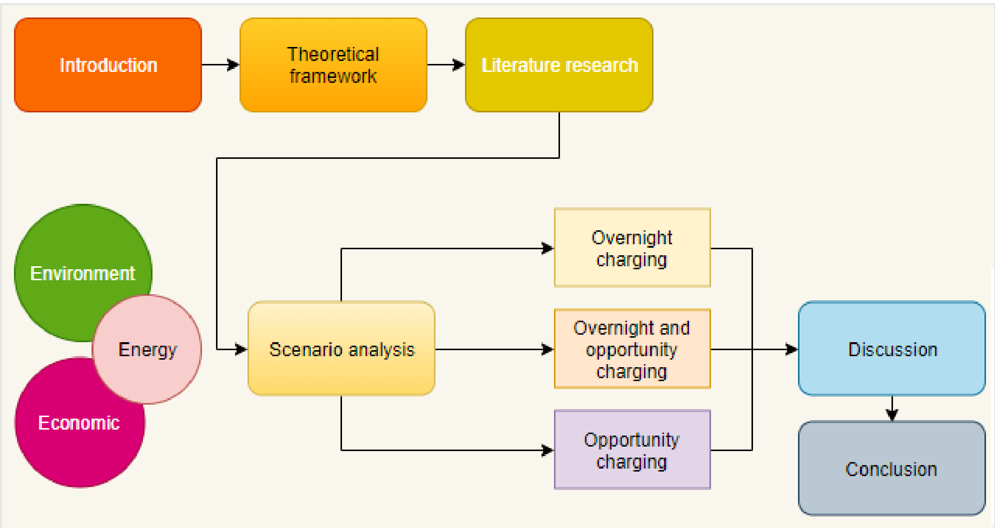



*Figure 2 The thesis structure*

# 2. Theoretical framework

*This chapter presents the literature that will be used to answer the research question. The aim is to provide a theoretical framework for the sustainability assessment conducted in this thesis. First, sustainability related theories and concepts are presented and the relevance of circular economy in supply chains is being explained. Thereafter, the theoretical basis of input-output modeling is being described, followed by a review of previous EIO studies. The chapter ends with a review and discussion of the developed theoretical framework.*

## 2.1. Sustainability

In this section, the theory that is necessary to assess the sustainability of supply chains is being covered. Sustainability is the core of this thesis and is therefore discussed in terms of environment, economic and sustainability. Furthermore the relevance of circular supply chains is being explained.

### 2.1.1. Triple Bottom Line (TBL) perspective

Sustainability has increased its influence in supply chain management and operation practices and has become very important in present time. This is due to the fact that organizations are increasingly held responsible for the environmental and social performance by majors stakeholders, in addition to increased demands of strong economic performance. Many definitions exists for sustainability in the literature: i) a system of policies, beliefs, and best practices that will protect the diversity and richness of the planet's ecosystems, foster economic vitality and opportunity, and create a high quality of life for people (Hill, 2009); ii) the endurance of systems and processes (regions, cities, industrial ecosystems, production zones, companies, supply chains, production processes) and iii) an overarching conceptual framework that describes a desirable, healthy, and dynamic balance between human and natural systems (Hill, 2009). Central to these definitions is sustainability's applicability to three elements of life: economic considerations, environmental protection and stewardship, and community and individual human well-being. Sustainability is a common important goal of businesses, governments and many organizations, yet measuring the degree to which an organization is sustainable is difficult. John Elkington strove to measure sustainability in the late 1990s by encompassing a new framework called the Triple Bottom Line. This framework, then, went beyond the traditional measures of economic performance by incorporating environmental and social dimensions. The TBL dimensions are also commonly called the three Ps: people, planet and profits. The TBL can be defined as an accounting framework that incorporates three dimensions of performance: social, environmental and economic (Slaper & Hall, 2011). The social dimension includes the company's impact on its employees and the social system within its community. Social variables refer to social dimensions of a community or region and could include measurements of education, equity and access to social resources, health and well-being, quality of life, and social capital. The environmental line of TBL refers to engaging in practices that do not compromise the environmental resources for future generations. Environmental variables represent measurements of emissions, waste, recycling and natural resources. It could incorporate air and water quality, energy consumption, utilization of natural resources, solid and toxic waste, and land use/land cover. The economic dimension focuses on the economic value provided by the organization to the surrounding system in a way that prospers it and promotes for its capability to support future generations. This dimension deals with the bottom line and the flow of money. Economic variables are related to income or expenditures, taxes, efficiency, quality, business climate factors, employment, and business diversity factors. Potential sustainability indicators for each dimension are identified through the analysis of existing studies (Table 1). There is no common standard method for calculating the TBL. Mintz (2011) recommends that organizations develop key performance indicators (KPI) or quantifiable measures linked to their own missions, goals, and stakeholder expectations. Additionally, the TBL is able to be case or project specific or allow a broad scope—measuring impacts across large geographic boundaries—or a narrow geographic scope like a small town. A case or project specific TBL would measure the effects of a particular project in a specific location. The TBL can also apply to infrastructure projects at the state level or energy policy at the national level. The level of the entity, type of project and the geographic scope will drive many of the decisions about what measures to include. Nevertheless, the set of measures, will ultimately be determined by stakeholders and the ability to collect the necessary data. Appendix B presents per sustainability dimension examples of measures that can be used to quantify the sustainability indicators. TBL does not have a common unit of measure. Some advocate monetizing all dimensions of the framework, while others encourage the use of an index. Businesses, nonprofits and government entities alike can all use the concept of the TBL. The framework can be used by communities to encourage economic development growth in a sustainable manner (Slaper & Hall, 2011). Challenges to putting the TBL into practice are measuring each of the three categories, finding applicable data and calculating a project or policy's contribution to sustainability.

| Economic | Environment | Social |
|---|---|---|
| Productivity | GHG emissions | Change in income |
| Personal income | Waste reduction | Employment |
| Revenue by sector contributing to gross state product | Use of post-consumer and industrial recycled material | Training |
| Percentage of firms in each sector | Percentage of materials/products recycled | Accidents |
| Amount of taxes paid | Energy consumption | Job creation |
| Quality of product/service | Inventory of land use | Noise reduction |
| Job creation | Public transportation ridership | Working conditions |
| Cost reduction | Fuel consumption | Timing and location |

*Table 1 Indicators for economic, environment and social sustainability*

### 2.1.2. Sustainable supply chains (SSC)

Many sustainable supply chain management frameworks have been emerging in the last decades, which are primarily underpinned by product life cycle influences and operational influences (Genovese, Acquaye, Figueroa, & Koh, 2017). The requirement to take holistic view of the whole product supply chain has become an important step for establishing more sustainable production systems, based on reusing and remanufacturing materials. Sustainable supply chain is the management of material, information and capital flows as well as cooperation among companies along the supply chain while taking goals from all three dimensions of sustainable development, i.e., economic, environmental and social, into account which are derived from customer and stakeholder requirements (Seuring & Müller, 2008). A focus on supply chains is a step towards the broader adoption and development of sustainability, since the supply chain considers the product from initial processing of raw materials to delivery to the customer. However, sustainability also must integrate issues and flows that extend beyond the core of supply chain management: product design, manufacturing by-products, by-products produced during product use, product life extension, product end-of-life, and recovery processes at end-of-life. The components of a supply chain life cycle are summarized in Figure 3. Consideration of the extended supply chain is important in the reduction and elimination of by-products through cleaner process technologies. From the industrial ecology literature and increasingly considered by manufacturers is the use of by-products of manufacturing such as waste as an input for other production processes or supply chains. This SSC is an example of an industrial symbiosis based supply chain. Industrial symbiosis has been defined as engaging "traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and by-products. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity" (Chertow, 2007). There are many factors that influence the sustainability of a supply chain, including the suppliers of the materials and energy used in the production, the modality of supply and the technology used in the production of the product/service and its components. Hence, when designing a supply chain, it is important to consider the sustainability of production inputs and outputs, the location and sustainability of the suppliers, the transportation methods between the processes in the supply chain and the end-of-life strategy.

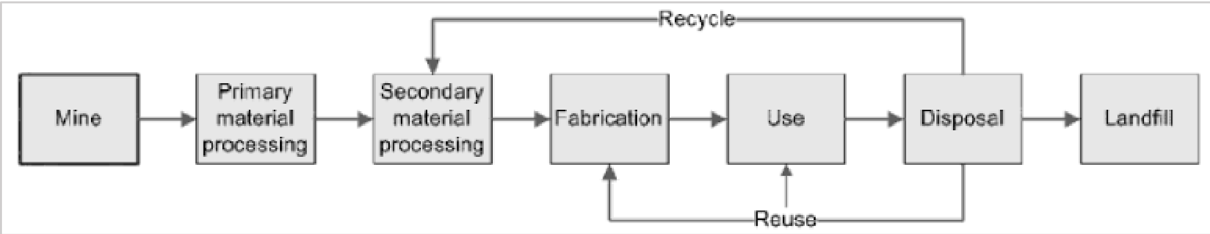



*Figure 3 A generic supply chain life cycle model*

### 2.1.3. Supply chains in circular economy

Circular Economy (CE) is defined as a global economic model to minimize the consumption of finite resources that focuses on intelligent design of materials, product and systems (Ellen Macarthur Foundation, 2013). The concept sustainable supply chain management has been developed in parallel to the circular economy discourse, which has been propagated in the industrial ecology literature and practice for a long time. In fact, sustainable supply chain management seeks to integrate environmental concerns into organizations by minimizing materials' flows or by reducing unintended negative consequences of production and consumption processes (Genovese, Acquaye, Figueroa, & Koh, 2017). The paradigm of circular economy seeks to continually sustain the circulation of resources and energy within a closed system (the planet) thus reducing the need for new raw material inputs into production systems. The principles of circular economy thus reveal an idealistic ambition of pushing the boundary of sustainable supply chain management practices. In this context the concept of Reverse Supply Chain Management has been developed as an adaptation of circular economy principles to supply chain management. Indeed, a reverse supply chain includes activities dealing with product design, operations and end-of-life management in order to maximize value creation over the entire lifecycle through value recovery of after-use products either by the original product manufacturer or by a third party. Reverse supply chains are either open-loop or closed-loop. Basically, open-loop supply chains involve materials recovered by parties other than the original producers who are capable of reusing these materials or products. Nowadays, given the constraints relative to the availability of non-renewable resources (metal, oil, etc.), enterprises are more than ever obliged to rethink their strategies to ensure the sustainability of their operations. Closed-loop supply chains deal with the practice of taking back products from customers and returning them to the original manufacturer for the recovery of added value by reusing the whole product or part of it. Basically there are different types of circular business models, indicating a different type of closed loop. Bocken et al. (2016) identifies two different models, towards resource loops, namely extending the utilization period of the product, which slows down the resource loop, and recycling, which closes the resource loop. In the recycling process, the identity and function of a product or component are not to be preserved, but the materials of the product and components are reused. Thierry et al. (1995) have identified different product recovery activities, including repair, refurbishing, remanufacturing, cannibalization and recycling. Main differences between these product recovery options are related to level of disassembly and quality requirements. Figure 4 presents the integrated supply chain where service, product recovery, and waste management activities are included. Returned products and components can be resold directly, recovered, or disposed {incinerated or landfilled). The options are listed in order of the required degree of disassembly.

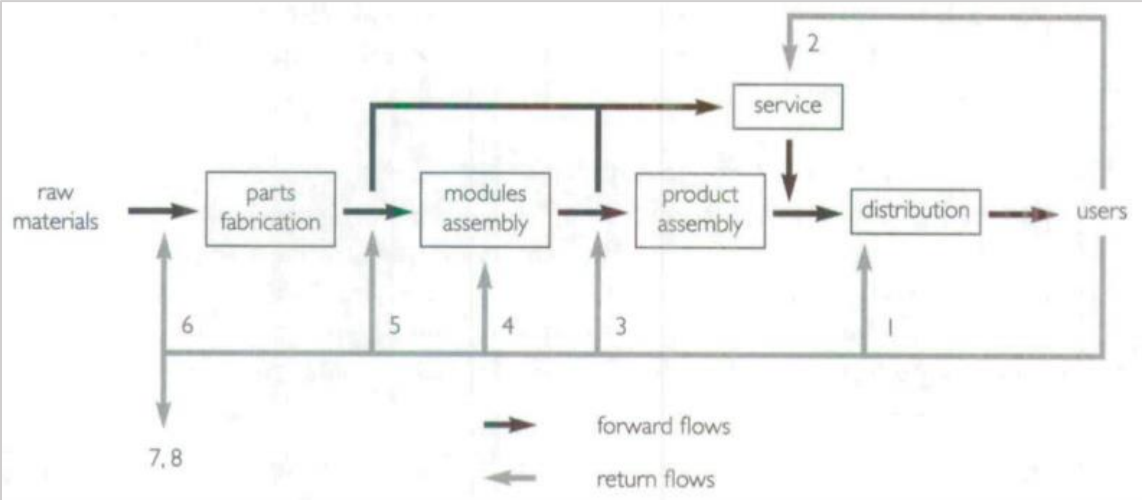



*Figure 4 Integrated supply chain* (Thierry, Salomon, Van Nunen, & Van Wassenhove, 1995)*; Processes in the chain are direct reuse (1), repair (2), refurbishing (3), remanufacturing (4), cannibalization (5), recycling (6), incineration (7) and landfilling (8).*

Central to the concept of circular economy is that the value of materials and products is kept as high as possible for as long as possible (EEA, 2018). This helps to reduce new material input and energy needs throughout a product's life cycle. The benefits are usually higher for what can be considered 'inner circle' approaches — reuse, repair, redistribution, refurbishment and remanufacturing — than for recycling and energy recovery (EEA, 2017). This is due to losses during collection and processing and to degradation of material quality during recycling. Relevant aspects of this 'closed loop system' include:

- products designed to reduce waste and pollution;
- keeping products and materials in use for as long as possible/feasible;
- remanufacturing and recycling of goods;
- regeneration of nature systems — providing a focus on natural capital;
- use of renewable energy;
- sustainable consumption, e.g. through shared ownership of goods.

## 2.2. Enterprise input-output (EIO) modeling

In this section the existing research about input-output modeling within Industrial Engineering is presented, which is being used to form the methodology this study utilizes.

### 2.2.1. Introduction

We focus on the material/energy/waste flows during the manufacturing and operation phases using the framework of the input-output model (IO model). The IO model has been traditionally used to analyze monetary flows in nations or regions (Leontief W. W., 1936) and has also been applied to energy flow analyses within nations (Leontief & Ford, 1970). The input-output model described in this thesis is intended for application to the corporate level and is therefore referred to as an enterprise input-output model (EIO model). EIO models are a set of IO models which are useful to complement managerial, environmental, and financial accounting and planning systems.
The input-output model divides an entire economy into distinct sectors and can be visualized as a set of tables. Such tables include a series of rows and columns of data that quantify the supply chain for all sectors of an economy. Each sector of the economy is represented by one row and one column. Figure 5 shows the structure of an input-output model. Each entry $z_{ij}$ represents the input to sector j

from sector i in the production process. The total output of each sector $x_i$ is the sum across the rows of the inputs from the other sectors, the intermediate output $\sum z$ and the output supplied to final demand by consumers. The gross domestic product (GDP) is the sum of all the final demands. Within the input-output table, the column sum represents the total amount of inputs to each sector from other sectors. The IO model is linear, so that the effects of a €1000 purchase from a sector will be ten times greater than the effects of a €100 purchase from the same sector. An IO model records the flows of resources from each industrial sector considered as a producer to each of the other sectors considered as consumers. An IO model is therefore a matrix representation of all the economic activities taking place within the supply chain. The IO table provides information on the inputs used and outputs generated in each in-company sector. Four types of flows can be modelled:

- Primary inputs, which are purchased from outside the supply chain (labor, capital, land);
- Main inputs, which come from other processes belonging to the supply chain, namely intermediate deliveries (outputs produced by other processes);
- Main output, which is produced by the supply chain process; and
- Wastes and by-products produced as secondary outputs by the processes of supply chain

| | A. INTERMEDIATE FLOWS (Z) | | | | | B. FINAL DEMAND (f) | x |
|---|---|---|---|---|---|---|---|
| | Agriculture 1 | Manufacturing 2 | Transportation 3 | Service 4 | Total interm. flows | Final demand | TOTAL OUTPUT |
| 1 Agriculture | $z_{11}$ | $z_{12}$ | $z_{13}$ | $z_{14}$ | $\sum_j z_{1j}$ | $f_1$ | $x_1$ |
| 2 Manufacturing | $z_{21}$ | $z_{22}$ | $z_{23}$ | $z_{24}$ | $\sum_j z_{2j}$ | $f_2$ | $x_2$ |
| 3 Transportation | $z_{31}$ | $z_{32}$ | $z_{33}$ | $z_{34}$ | $\sum_j z_{3j}$ | $f_3$ | $x_3$ |
| 4 Service | $z_{41}$ | $z_{42}$ | $z_{43}$ | $z_{44}$ | $\sum_j z_{4j}$ | $f_4$ | $x_4$ |

*Figure 5 Example structure of an enterprise input-output table*

The proportional input from each sector for a unit monetary output can be represented in a different table, called the technology coefficient matrix. This table, basically, describes the technology (raw materials, energy, machinery, transports, services) of a given industry which is characterized by the mix of supply chain inputs required to product a unit output. This table is calculated by dividing each $z_{ij}$ entry by the total output of the sector.

The technology coefficients show the amount of input required for each unit of output and are mathematically obtained as: $a_{ij}^{s} = \frac{X_{ij}}{X_j}$ and $a_{ij}^{e} = \frac{Y_{ij}}{X_j}$

Let $Z_0$ be the matrix of domestic (i.e. to and from production processes within the supply chain) intermediate deliveries, $f_0$ is the vector of final demands, and $x_0$ the vector of gross outputs. We define the result table with entries between zero and one as the technology coefficient matrix A, showing the output flow from sector i to sector j required to produce one unit of output of sector j. The intermediate coefficient matrix A is defined as follows:

$$A = Z_0 \hat{x}_0^{-1}$$

where $\hat{x}_0$ is used to denote a diagonal matrix. Algebraically, it can be shown that the requirements in all actors in the supply chain to make a vector of desired output $f_0$ can be calculated as:

$$x_0 = (I + A + A \times A + A \times A \times A + \cdots)\, f_0 = (I - A)^{-1}\, f_0$$

where $x_0$ is the required inputs, I is de identity matrix, and A is the input-output direct requirements matrix. This formula represents the production of the desired output itself ($I \times f_0$) and the direct

$(A \times f_0)$ and indirect supplies $(A \times A \times f_0)$ and can be used to estimate the outputs required to produce a specified set of products. The total of these outputs can be considered as the supply chain. There are also *m* byproducts and/or wastes in the supply chain. Let $r_0$ be the primary input vector (size s x 1) and $w_0$ be the by-product/waste vector (m x 1). Let R be the s x n matrix of primary input coefficients with the element $r_{kj}$ denoting the use of primary input k (1,..., s) per unit of output of process j and let W be the m x n matrix of waste and by-product coefficients, with the element $W_{lj}$ denoting the output of by-product or waste type l (1,..., m) per unit of output of process j. It results:

$r_0 = R \times x_0$

$w_0 = W \times x_0$

To calculate the monetary flows, we define the unitary price and the price vectors. Let $p_0$ be the vector (n x 1) of the prices with element $p_i$ denoting the unitary price of the main product of the process i. Hence, using the vector of gross outputs $x_0$, we can calculate the vector $y_0$ (n x 1), representing the total revenues associated with each gross output as follows:

$y_0 = \hat{x}_0 \times p_0$

Furthermore, the monetary input-output matrix B (n x n) can be defined, where the generic element $b_{ij}$ is expressed as:

$b_{ij} = a_{ij} \times \frac{p_i}{p_j}$, so that $y_0 = By_0 + \hat{f}_0\, p_0 = (I - B)^{-1} \hat{f}_0\, p_0$

### 2.2.2. EIO models for supply chains

A supply chain represents an integrated process wherein a number of various business entities (i.e. suppliers, manufacturers, distributors, and retailers) work together to acquire raw materials, convert them into specified final products, and deliver final products to retailers (Polenske, 2001). The supply chain of any company can be described in terms of production processes whose material/energy flows are represented in physical terms. A simple representation of a supply chain process from an input-output perspective is given in figure 6. Input-output approach has been typically applied to analyze the economic structure of regions in terms of flows between sectors or firms. For a supply chain, the processes of the network belong to different firms, from the raw materials suppliers to the final customer. Each process requires various raw materials and components produced by other processes of the supply chain as well as a certain quantity and type of energy. An input-output approach based on processes can be used to develop specific input-output process models that analyzes the complex network of materials, energy and pollution flows that characterize the supply chain of a final product.

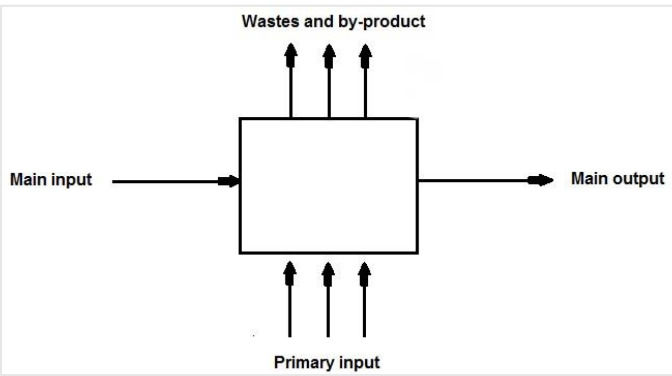



*Figure 6 A supply chain process from an input-output perspective*

Two types of supply chains can be distinguished: global and local supply chains. Global supply chains are networks of processes that procure raw materials, transform them into intermediate goods and then final products, and deliver the products to customers through distribution systems. Local supply chains refer to processes localized within a geographic area. The input–output approach can be used to analyze only the flows (of raw materials, energy, products, pollution, imports and exports) relative to the processes of the chosen local supply chain, but also the relationships among these processes and those belonging to other enterprises (global supply chain). Within local production systems, twofold level of analysis are available in the view of implementing a local sustainable development: the micro level of a single company or the more aggregated level of a whole district (Albino & Kühtz, Enterprise input–output model for local sustainable development—the case of a tiles manufacturer in Italy, 2004). The micro level helps a single company in making suitable choices consistent with its sustainable development, while the aggregated level analyses all the local area and can support stakeholders in developing policies for local infrastructures enhancement, and for energy and resources conservation and waste reduction.

Input-output models can be effective to negotiate a common policy for the management of resources and wastes at supply chain level as well as at local level. For a given final product output, the computation of materials, energy and waste flows provides a measure of resource consumption and the environmental impact of processes (Albino, Izzo & Kühtz, 2002). Changes either in the final product output or in the technologies adopted by each process, or else in the process location can easily be planned and their effects on the supply chain management and on the local environment can be analyzed. The measure of the environmental impacts of an industrial district can be based on the input-output accounting model proposed for the economic- energy-environment analysis of an industrial district (Albino, Dietzenbacher & Kühtz, 2003).

### 2.2.3. Summary of EIO studies

The input-output approach based on production processes, as described in Albino et al. (2002) can be used: (i) to recognize functional relationships among flows of processes in a local and global supply chain, (ii) to determine the processes that contribute more to environmental pollution, and, (iii) to evaluate how one can change the input mix or the imports rate (for instance of energy sources) in order to respect environmental constraints (e.g., to reduce pollution, keeping other output flows constant). Albino et al. (2002) has formulated input–output models to map production activities, to interrelate and estimate flows of energy and materials, including use and consumption of fuels and production of pollutants within the supply chain of a final product. This model has also been applied by Albino & Kühtz (2004) to the supply chain of an existing Italian tiles manufacturer and is adopted in the first place as an accounting tool and secondly as a decision support system. In their research, the model is used in the first place as an accounting tool via the input–output balance tables that account for materials, energy and consequent waste/pollution emissions thus providing a measure of the environmental impact of the company. As second, it is used as a planning tool, to foresee possible development scenarios. The enterprise input–output model presented in this work is very easy to implement, extremely flexible, allows to evaluate the environmental impact of companies and provides a measure of resources consumption and wastes destination. Küthz et al. (2010) uses the EIO approach to analyze the flows (i.e. raw materials, energy, products, wastes, etc.) relative to the production cycles of the chosen tile manufacturing lines to the determine the processes that contribute most to environmental pollution and to evaluate how one can change the input mix (for instance of energy sources) in order to respect environmental constraints (e.g. to reduce energy use, keeping other output flows constant).

# 3. Literature research

*In this chapter, the relevant bus and charging technologies are discussed in terms of their technological characteristics and environmental and economic benefits and drawbacks. Furthermore, the most important factors that impact the energy consumption of the battery buses is presented. Finally, the most common batteries are discussed in terms of composition, lifetime and end-of-life treatment.*

## 3.1. Bus and charge technologies

The following section describes the technological characteristics and environmental and economic benefits and drawbacks of the bus and charging technologies that are included in the thesis. Furthermore, the factors that have an impact on the consumption are explained.

### 3.1.1. Battery buses

Battery buses are pure battery electric vehicles (BEV) that have an on-board battery which stores energy previously taken from the electric grid and powers an electric drivetrain, which includes an electric motor driving the car wheels. The principal features distinguishing BEVs from ICEVs are the components for energy storage, propulsion and braking. In place of the fuel tank, engine, gearbox and exhaust found in ICEVs, BEVs require a battery, an electric motor and power electronics. The electric motor is particularly efficient and regenerative braking provides further efficiency gains. Regenerative braking systems help keep the battery in an electric vehicle charged, by converting into electricity much of the energy that would normally be lost as heat through traditional braking. Figure 7 presents the simplified layouts for the configurations of the conventional and electric powertrains. Currently, other components, such as the vehicle body and auxiliary systems, do not necessarily differ. Many existing BEVs are adapted from ICEV vehicle bodies to save on development time and costs and to take advantage of existing production lines. Like conventional vehicles, electric vehicles incorporate several types of auxiliary equipment. These include power steering, braking support, passenger cooling and heating systems, and battery heating and cooling systems. Especially during cold periods, both the battery and passenger heating systems can consume much of the battery capacity, potentially reducing driving range.

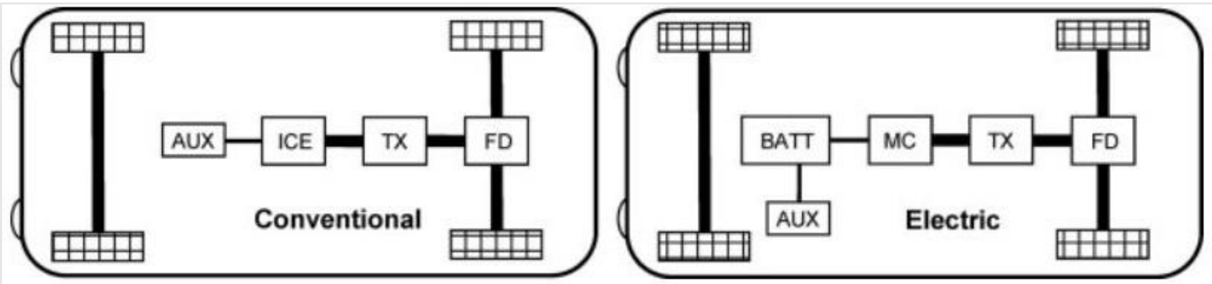



*Figure 7 Simplified layout of an electric bus configuration (BATT = battery, ICE = diesel engine, MC = motor/controller, TX = transmission, FD = final drive, AUX = auxiliary devices (Lajunen A. , 2014))*

Battery electric vehicles have batteries adapted for external charging, no internal combustion engine and drive purely on electric energy. At present, lithium-ion batteries are the most common type of batteries used in electric vehicles (EEA, 2016). These batteries are lighter and smaller than other rechargeable batteries for the same energy storage capacity and have an outstanding combination of high energy and power density, making it the preferred technology for hybrid and electric vehicles (Nitta, Wu, Lee, & Yushin, 2015). The energy density (energy capacity per weight and size) of batteries is rather low compared to diesel or hydrogen (Campanari, Manzolini, & De la Iglesia, 2009). The driving range of battery buses is therefore limited and the charging process requires a certain time. Because of the capacity limitations of electrical energy storages, electric buses need to have a large amount of stored energy on-board or the storages are needed to be recharged during operation (Rogge, Wollny, & Uwe Sauer, 2015). Research has been increasingly done in this field to define the technical requirements for the bus technology and charging infrastructure. The battery and charging power requirements were evaluated in Rothgang et al. (2015) and Rogge et al. (2015). The local operating situation and requirements have important influence on the battery system design and charging concept choice of electric buses (Rothgang, Rogge, Becker, & Sauer, 2015). The limiting factor for the installable battery capacity in an electric bus is the weight of the bus. The smaller the battery, the greater the number of passengers that can be transported and the more often the battery needs to be recharged. Thus, it is a tradeoff between passenger and battery capacity. In addition, there is a tradeoff between the capacity of the battery (kWh) and the charging power (kW). The required battery capacity decreases with an increasing charging power. Rogge et al. (2015) addresses these tradeoffs and concludes that a reduction of the demanded passenger capacity enables an increase of the installable battery capacity, so that the required charging power can be reduced. Furthermore, their analysis points out that it is necessary to focus on the entire vehicle schedules instead of individual trips, when the required battery size is calculated.

Among the lithium-ion battery chemistries, there is a division to high-power and high-energy battery chemistries. For the case of fast charging, power optimized batteries are used in electric vehicles, while for the case of slow charging energy optimized batteries are preferred (Xylia, et al., 2019). Power optimized batteries have high specific power (kWh/kg) and can accept high currents which is required for fast charging applications. These batteries have lower energy density, can withstand higher charging power and have a longer life than energy optimized batteries. Energy optimized batteries, on the other hand, have a higher energy density and therefore can store more energy (kWh/kg). Buses that only make use of overnight charging are known to have a larger battery package compared to buses that recharge during operation. With the end station and opportunity charging, the on-board battery capacity does not need to be very high in comparison to overnight charging (Lajunen & Lipman, 2016). Higher battery capacity allows flexibility for using different charging strategies e.g. minimizing charge demands by lowering charging power. Lajunen (2018) shows that high energy capacity of the battery system is crucial for the overnight charging buses to achieve adequate daily operation whereas the battery size has a minor impact on the energy consumption and lifecycle costs of the fast charging buses.

### 3.1.2. Electric charging techniques

The limited driving range of many electric vehicles means that the type of technology used to charge them, and the time it takes, are very important. The electric buses currently operating in the Netherlands allows us to categorize these buses based on their charging technique. Two types of buses can be observed: slow charging buses and slow-and-fast charging buses. Buses that make use of overnight charging are known with slow charging, which means that they are slowly charged at the depot after bus operation is finished. Slow charging is performed with a moderate charging power overnight and during longer brakes. This causes a high battery capacity and a high weight of the system, when the bus shall be operated the entire day (Sinhuber, Rohlfs, & Sauer, 2012). Slow chargers are placed in the depots to charge both plug-in, opportunity charging buses and in motion charging (IMC) buses at night. The buses using both slow and fast charging are charged at night and during operation. Hence, these buses make use of overnight charging and opportunity charging, which happens at the station or the bus stops. Fast chargers are used to recharge public transportation buses during operation. Fast charging on the track during operation can reduce the battery capacity and therefore the weight significantly. However, the bus schedule must provide sufficient charging times at certain locations. Charging at night on the depot is also called depot charging and charging during the day on high power is called opportunity charging. The most important differences between these two charging methods are the power and the moments at which one loads (Elaad, 2017). In both cases, charging takes place while standing still, so that the buses are not standing still to charge. Unnecessary stopping leads to costs and hence is kept to a minimum. The choice of a charging strategy depends on various factors, such as: number of kilometers per day, costs, predictability, passenger capacity per bus and flexibility. Overnight charging is preferred in case the number of kilometers traveled per day is small enough, so that investment in extra chargers on the road is not necessary. Lajunen (2018) shows that overnight charging may not be suitable for all types of operating routes due to the limitations of battery energy capacity. High energy capacity of the battery system is crucial for the overnight charging buses to achieve adequate daily operation. With opportunity charging, less battery capacity, but more charging points and time in the schedule is needed to load.

### 3.1.3. Factors affecting energy consumption

In order to quantitatively analyze the environmental benefits, it is essential to explore the energy consumption behavior of electric buses during the usage phase. Initial studies suggest that the energy consumption of electric vehicles is influenced by a wide range of factors. For electric buses to serve their purpose as public transit vehicles, it is important that they can operate reliably in a range of weather conditions. For instance, the temperature in different climate zones can influence the drivetrain efficiency and can lead to an increasing energy demand as a result using heating and or cooling (Travesset-Baro, Rosas-Casals, & Jover, 2015). As the temperature decreases, the energy consumption increases. Furthermore, the buses charge more slowly when it is cold and their voltage supply weakens when operating in temperatures lower than their optimum.

The factors that have an impact on the energy consumption of electric vehicles that can be found in the literature are related to technology and vehicle, artificial and natural environment, driver's aggressiveness and travel type. Critically, no empirical model is available to depict these influences and predict the consumption according to the area of use (Egede, Dettmer, Hermann, & Kara, 2015). With respect to technology and vehicle, the main factors that influence the energy consumption are the battery and the heating, ventilation and air conditioning (HVAC) system of the buses. The frequency and depth of battery cycles are important as they determine the lifetime and efficiency of the battery. Due to the absence of combustion engines, either PTC (Positive Temperature Coefficient) heater or heat pump is needed to generate heat which requires a higher energy than air conditioning in principle. Nevertheless, the actual consumption is highly associated with the local climate and driver's behavior (Li, Stanula, Egede, & Herrmann, 2016). The surrounding conditions influence the environmental impact of EVs. The artificial environment factors include the infrastructure and the environment related to humans, such as traffic and intersections. With respect to traffic, the higher the level of congestion, the higher is the overall consumption. The higher the traffic, the more a vehicle has to decelerate and accelerate because of several stops and the variation of speed, hence the consumption rises. The natural environmental factors include the topography of a region, the climate zone and the weather and are identified as significant factors for the energy consumption. The ambient temperature and humidity are correlated to the use of the heater and air conditioning. For topography, the following generally applies: the higher the variance of altitude, the higher is the consumption due to the need to overcome the additional vertical force (Younes, Boudet, Suard, Gérard, & Rioux, 2013). Egede et al. (2015) categorizes the parameters on which the energy consumption of electric vehicles depends into three groups: driving resistances, the use of auxiliaries and losses. Driving resistances must be overcome to achieve and maintain a certain velocity. Examples are the rolling, acceleration and aerodynamic resistance. Vehicle characteristics like weight and the frontal area influence the resistances. The weight of the vehicle affects directly the rolling and climbing resistance and has therefore a strong impact on the energy consumption. Furthermore, losses occur in the process of converting electric energy into mechanical energy due to the efficiencies of the different components.

Zhou et al. (2016) demonstrates substantial impacts of operating conditions on the real-world energy consumption for battery buses, and showed that the operating conditions are highly associated with local traffic and weather conditions, as well as the driving behaviors of bus operators. A battery electric bus tends to achieve higher fuel saving potential over a diesel bus under difficult conditions, such as heavy traffic, air conditioning operation, and a full passenger load. Air conditioning contributes more to the battery bus's electric consumption than passenger load in multiple scenarios. Zhou et al. conclude that battery buses' well to wheel environmental benefits increase when operating under worst-case conditions, such as heavy traffic, full passenger load, and air conditioning usage.

Lajunen (2018) shows that the energy consumption depends on the weight of the bus, weather conditions and the operating route. The weight of the bus is dependent on the battery capacity and influences the energy consumption. A reduction of the weight of a BEV and the related electricity consumption will drastically reduce the impacts linked to electricity generation. A weight reduction should come from the substitution of the steel chassis with a material with a lower weight and from increasing the energy density of the battery (Messagie, 2014). Operating in cold climate conditions could increase the energy consumption significantly if the bus heating power is drawn from the battery. However, it was shown in another research study that the average increase of the energy consumption due to the weather conditions over a year of operation was only 10% (Lajunen & Lipman, 2016). The research shows that overnight charging buses have on average 10% higher energy consumption than the fast charging buses, which is mainly due to the higher auxiliary power consumption. It seems that higher auxiliary power increases the lifecycle costs up to 10% for end station charging buses and up to 30% for opportunity charging buses.

### 3.1.4. Environmental considerations

There are no exhaust emissions while driving a battery electric vehicle. This helps to improve local air quality. Both battery electric vehicles (BEV) and fuel cell electric vehicles (FCEV) are often regarded as the only long term complete solution to the problem of pollution in urban areas, as well as to the problem of $CO_2$ emissions, thanks to the use of clean energy vectors like electricity and hydrogen: in principle, the electricity used by BEVs or the hydrogen used by FCEVs (at least in the option where it is not produced onboard) could be generated by clean and $CO_2$-free processes, using renewable sources or nuclear energy or fossil energy with $CO_2$ capture and storage techniques (Campanari, Manzolini, & De la Iglesia, 2009). Their analysis shows that (i) when using 100% renewable energy sources to generate electricity, the BEV is the most efficient option; when using an average primary source mix in electricity generation, the BEV performances are much lower, and the FCEV solutions become much more favorable both by the point of view of efficiency and $CO_2$ emissions.

Most of the current decision-making relies on analysis at the tailpipe, ignoring vehicle production, infrastructure provision, and fuel production required for support. The energy and emissions associated with raw materials extraction and processing, supply chain transport, vehicle manufacturing, vehicle maintenance, infrastructure construction, infrastructure operation, fuel production, as well as many others should be included in any environmental inventory to comprehensively evaluate the energy use or emissions of a mode (Chester & Horvath, 2009). Mostly life cycle assessment (LCA) is used to quantify the environmental impact along the entire life cycle from raw material extraction to the end-of-life. However, calculating the environmental impact with a LCA for electric vehicles is challenging. Hawkins et al. (2012) performed a literature review in which they reviewed 51 environmental assessments to understand how well existing studies of the environmental impacts of hybrid and electric vehicles address the full life cycle of these technologies. They conclude that the overall gaps in existing environmental assessments of EVs are significant. Only a small percentage of the reviewed studies cover all stages of the life cycle of electric vehicles with assessment of multiple impacts. Research has focused on well to wheel studies comparing fossil fuel and electricity use as the use phase has been seen to dominate the life cycle of vehicles. The LCA studies come in many shapes and cause diverging arguments about the environmental performance of the technology on which they are based. The reasons of divergence in the literature is caused by 1) variations in the system boundaries, 2) differences in allocated average or marginal electricity mixes, 3) the usage of New European Driving Cycles (NEDC) or real life monitored tailpipe emissions for comparisons, 4) assumptions made about the lifetime of the vehicles or batteries (Messagie, 2014). Choosing a shorter lifetime of the battery increases the relative importance of the battery production stage, and therefore the battery lifetime is considered very important in the environmental assessment of electric vehicles.

A large share of the environmental impact of the EV occurs in the use phase and is directly linked to the energy consumption during usage in combination with the energy mix. In fact, the environmental impact of bus transportation is dependent on the energy consumption. The environmental impacts of electric vehicles depend on various parameters related to the vehicle's characteristics, their location of use and user influences. Variations of driving patterns of different users and the use of heating and cooling due to local climate conditions have an impact on the energy consumption of EVs (see section 2.2.). The user of the electric vehicle influences the environmental impact of the EV through the driving and charging behavior as well as through the intensity of the use of auxiliaries. A more aggressive driving style leads to a higher energy consumption whereas a more cautious driving style results in a more efficient use of energy (Egede, Dettmer, Hermann, & Kara, 2015). Messagie (2014)) made a meta-model of the life cycle stages of an electric and conventional vehicle, consisting of four parts: 1) the fuel supply chain, 2) energy conversion in the vehicle, 3) manufacturing, maintenance and recycling of the vehicle and 4) the manufacturing of the motor, battery and electronics. Messagie (2014) concludes that 70% of the impact of the electric vehicles originates from the production of the electricity, the remaining 30% of the impacts is evenly split among the production of the vehicle (15%) and the lithium battery (around 15%). The single most important opportunity to improve the battery electric vehicles' impact lies in the supply mix of the electricity. A reduction of the weight of a battery electric vehicle and the related electricity consumption will drastically reduce the impacts linked to electricity generation. In the terms of total life cycle, the GHG impacts of EVs are heavily dependent on use phase energy consumption and the electricity mix used for charging (Hawkins, Gausen, & Strømman, 2012). Notter et al. (2010) shows that the environmental burdens of mobility are dominated by the operation phase regardless of whether a gasoline-fueled internal combustion engine vehicle (ICEV) or a European electricity fueled BEV is used. This finding is in good accordance with other studies showing that the impact of operation dominates in the transport service (Hawkins, Gausen, & Strømman, 2012)). According to Messagie (2014), the parameters that play a key role in the environmental impact of the production of a 1kWh lithium battery are: cycle life, calendric life, depth of discharge (DoD), efficiency and energy density. Peters et al. (2016) reviewed existing studies on the environmental impact of lithium-ion battery production. They conclude that the assumptions made by the reviewed studies concerning the parameters cycle life, internal efficiency and energy density are found to be equally relevant for the environmental life cycle performance of the batteries. Energy density does not need to be more relevant than improving battery lifetime or charge-discharge efficiencies from an environmental point of view. The majority of battery-LCA studies focuses on climate change and energy demand, but other impact categories, mainly toxicity, are also relevant. Toxicity levels are primarily a function of the mining activities of the raw materials and the primary processes. Electric vehicles exhibit the potential for significant increases in the human toxicity, largely emanating from vehicle supply chain (Hawkins, Singh, Majeau-Bettez, & Stromman, 2013).

Xylia et al. (2019) evaluated the impact of large scale electrification on life cycle emissions of the Stockholm bus network. The results of their analysis show that, although higher battery capacities could help electrify more routes of the city's bus network, this does not necessarily lead to a reduction of the total emissions. This is due to the fact that batteries of higher capacity are larger and heavier, and lead to higher carbon emissions. Furthermore, the research shows that heavier batteries could not only lead to higher battery-related emissions, but also to higher fuel-associated emissions, as the energy consumption increases. The results of their research show that the lowest life cycle emissions occurs when electric buses use batteries with a capacity of 120 kWh. Another conclusion of their research is that the life cycle emission impact from batteries decreases at higher energy density values. Higher energy densities could help reduce the emissions associated with batteries, and support the electrification of a larger part of the bus network, as they would entail more energy per kg of battery. Finally, the results show that there is no completely emission-free solution when looking at the system from a life cycle perspective. In fact, even for the case of certified renewable electricity, there are emissions associated with the construction and operation of power plants, wind farms etc., as well as the life cycle impacts of batteries and various components used.

### 3.1.5. Advantages and disadvantages of BEVs

Studies clearly show that the electric buses can be much more energy efficient than conventional diesel buses (Lajunen & Lipman, 2016). The benefits of electric vehicles are the independence from fossil fuels, the reduction of noise and the elimination of tail pipe emissions. Electric motors have several advantages over conventional combustion engines. This includes their higher energy efficiency (an electric vehicle converts around 80% of the energy it uses to usable power, compared with around 20% for a conventional vehicle), high durability and quieter noise levels at low speeds. The efficiency advantage of BEVs arises partly because of the high efficiency of individual powertrain components (battery, motor, transmission;) and partly because of regenerative braking, which can supply roughly 10-20% of total energy used depending on driving style and conditions (Rangaraju, De Vroey, Messagie, Mertens, & Van Mierlo, 2015). The disadvantages of electric vehicles are mainly associated with the driving range and the cost of the vehicles (Egede, Dettmer, Hermann, & Kara, 2015). Currently, the driving range of electric vehicles is significantly lower than for conventional vehicles, however a large effort was done by the manufacturers to significantly extend the choice of electric vehicles during the last years (Berckmans, et al., 2017). EVs tend to have large batteries to maximize the energy storage capacity and hence allow longer driving ranges. Larger batteries provide greater energy storage and in turn vehicle range, however require more raw materials and energy to produce them, resulting in greater environmental impacts. The extra weight also leads to higher in-use energy requirements per kilometer. Furthermore, the use of heating and cooling devices can reduce the range significantly as the auxiliaries are very energy intensive. The main challenges in adopting electric buses are related to charging infrastructure development and high investment costs of buses. Hybrid and electric buses are more expensive to manufacture than conventional diesel buses (Lajunen A. , 2014). Most of the extra costs consist of the expensive electric components, such as battery, electric motor and power electronics, and the engineering development work especially on the system management. The price of the electric bus is influenced by the battery size. A battery represents 75% of an EV's powertrain cost (Wolfram & Lutsey, 2016), which means that implementing a bigger battery would significantly increase the overall cost. The purchase price of an electric bus, especially of an overnight charging bus, is therefore admittedly higher than that of a conventional bus, but the difference is largely covered by the lower costs of electricity. The costs of the charging infrastructure depend very much on the chosen charging strategy and the deprecation period. Various (feasibility) studies have indicated that the initial purchase and installation costs of the charging stations can be quite high. Lajunen (2018) presents a lifecycle cost analysis for a fleet operation of electric city buses in different operating routes. The research results show that the charging technique has an important role in the implementation of electric city bus operation and that the initial costs of the charging stations for opportunity charging are much higher than for overnight charging and end station charging. According to the lifecycle costs calculations, the end station charging buses have the lowest costs among electric buses.

The costs and durability concerns of lithium-ion batteries have a significant impact on the lifecycle costs of electric buses (Lajunen, 2014). The challenges with these batteries are that the costs are difficult to predict, since there are different battery systems and chemistries available and the battery technologies are still under development. In general, the costs of manufacturing lithium-ion batteries are high and the cost of the battery can be a significant fraction of the total electric vehicle price. The actual raw material cost of the lithium used makes up only a small fraction of the total battery costs, typically only up to 10 % of the total battery costs (Qnovo, 2016). Estimations for durability of lithium-ion batteries in city buses are somewhat hard to make because the operating conditions can vary a great deal in terms of the discharge and charge current demand, and temperature. Battery manufacturers typically define the life cycle performance in deep discharge-charge cycles in constant and low current rate conditions which may not correspond very well to the real operating conditions.

## 3.2. Batteries

This section covers the most common batteries in the market and compares the material composition of the batteries with each other. Moreover, the factors that influence the battery life are described and it is explained how the battery life can be approximated. The section ends with possibilities for used batteries after reaching end-of-life.

### 3.2.1. Lithium-ion batteries

Lithium-ion batteries have revolutionized the EV industry to become the preferred battery choice for EVs. This is due to their outstanding characteristics including high energy density, high voltage, low self-discharge rate, long cycle life, high charging and discharging rate capability. The main drawbacks of the currently available lithium-ion battery technologies are their still-limited energy density and the high manufacturing costs. While the detailed cost structure of manufacturing batteries is generally confidential, it is estimated that they break down into: material costs (60-66%), labor costs (5-15%), and the rest is manufacturing overhead and profit (Qnovo, 2016; Berckmans, et al., 2017). The costs of a battery is inversely linked with the growth of the market of electric vehicles, since larger production quantities leads to lowers cost per unit (Berckmans, et al., 2017). The market of electric vehicles (HEVs and BEVs) will have to increase by a factor of 52, which means a huge investment in battery manufacturing will be required to cope with this increase (Berckmans, et al., 2017). This mass production will be one of the driving forces of the decreasing cost of battery pack. The lithium-ion battery market is thought to have a compound annual growth rate of 14%, with the transport sector accounting for 60% of the market by 2025 (Drabik & Rizos, 2018). The continuously increasing appeal of this technology has caused a steep drop in price over the past years, which is likely to continue. The expected lithium-ion battery pack price in the following years is given in figure 8.

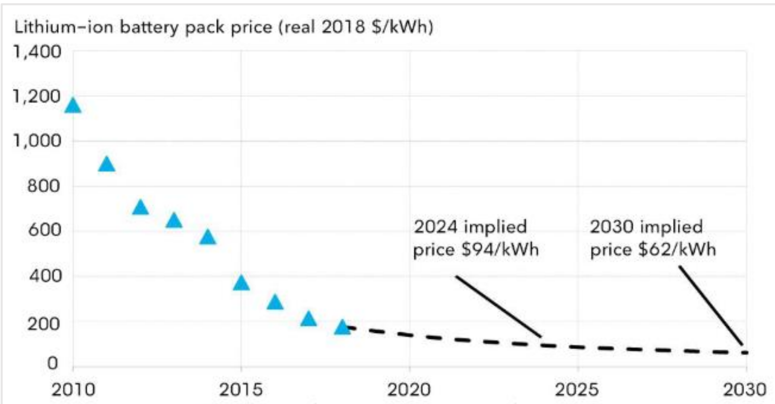



*Figure 8 Lithium-ion battery price outlook (BloombergNEF, 2019)*

### 3.2.2. Battery chemistries

The chemistry and cell construction of batteries are under intensive development resulting in improvements of temperature tolerances and lifetime. Since last couple of years, significant improvements have been achieved with lithium-ion batteries. The battery development has been towards increasing efficiency in materials and energy usage in production. Although there are different battery chemistries available, the main components of the battery system remains the same. The battery components can be grouped into four main components: battery cell, battery management system, cooling system and packaging. All of these components consist of subcomponents. The battery cell consists of five subcomponents: anode, cathode, electrolyte, separator and cell container. Figure 9 presents a simplified flow diagram of the battery system. Due to significant improvements to the lithium-ion batteries and various features used in applications, there are many lithium-ion type batteries on the market. Most of the improvements are technology related, like positive developments in the energy density of the battery. However, there are also improvements in environmental impacts and endurance.

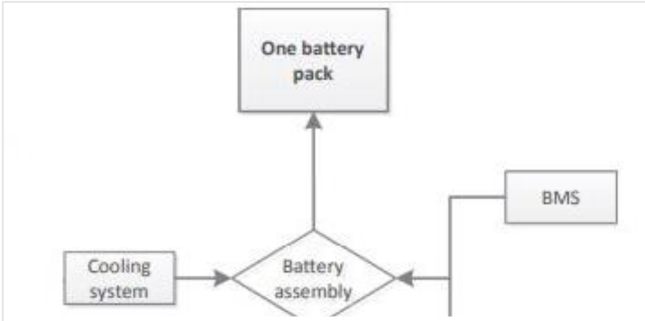
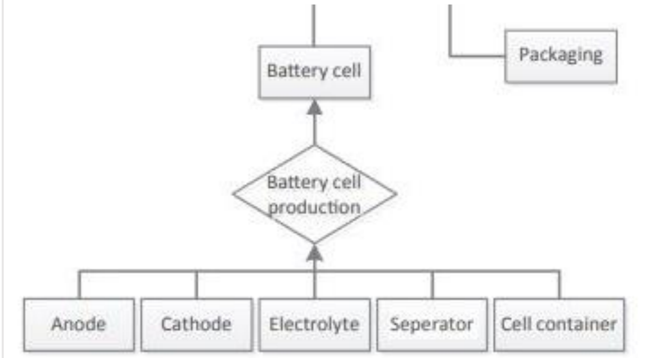



*Figure 9 Flow diagram of the battery system*




In general, the batteries can be differentiated based on the material composition of the cathode. The battery names are usually based on the cathode composition. Depending on the battery chemistry, the cathode contributes to at least 22% of the battery mass (figure 10). Most traditional batteries have cobalt as the main cathode component. However, due to the economic importance and supply risk of cobalt, the battery manufacturers have been minimizing the cobalt content of the lithium-ion batteries and even developing batteries that don't contain cobalt at all. There are a wide range of different li-ion battery technologies available and all of these could be considered as potential substitutes for the varieties that contain the most critical element at present: cobalt. The most commonly known type are lithium-nickel-oxide ($LiNiO_2$), lithium-manganese-oxide ($LiMnO_2$) and lithium-iron-phosphate (LFP). For the time being, in all of these potential substitutes the performance is considered to be lower than for the battery types that contain cobalt. The most common battery chemistries available in the market are $LiFePO_4$ (lithium iron phosphate), $LiNiCoMnO_2$ (lithium nickel cobalt manganese oxide) and $LiNiCoAlO_2$ (lithium nickel cobalt aluminium oxide), which have LFP, NCM and NCA cathodes respectively. The expectation is that there will be a continued shift towards NMC types of lithium-ion batteries, as the system can be built economically while still achieving a good performance (EEA, 2018) (Battery University, 2019). NMC is a cathode composition with nickel, manganese, and cobalt. Industry has been improving NMC technology by steadily increasing the nickel content in each cathode generation, while reducing the cobalt content.

| Battery | NCA-Graphite | LFP-Graphite | LMO (Spinel)-Graphite | LMO (Spinel)-TiO |
|---|---|---|---|---|
| Cathode | $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ | $LiFePO_4$ | $LiMn_2O_4$ | $LiMn_2O_4$ |
| Anode | Graphite | Graphite | Graphite | $Li_4Ti_5O_{12}$ |
| Battery mass (kg) | 75.9 | 81.6 | 62.6 | 106.2 |
| **Material Composition (mass %)** | | | | |
| Cathode active material | 24.8% | 22.2% | 24.4% | 28.3% |
| Anode active material | 16.5% | 15.3% | 16.3% | 18.9% |
| Electrode Elements | | | | |
| Lithium[b] (Li) | 1.9% | 1.1% | 1.4% | 2.8% |
| Nickel (Ni) | 12.1% | 0.0% | 0.0% | 0.0% |
| Cobalt (Co) | 2.3% | 0.0% | 0.0% | 0.0% |
| Aluminum (Al) | 0.3% | 0.0% | 0.0% | 0.0% |
| Oxygen (O) | 8.3% | 9.0% | 12.4% | 22.3% |
| Iron (Fe) | 0.0% | 7.8% | 0.0% | 0.0% |
| Phosphorus (P) | 0.0% | 4.4% | 0.0% | 0.0% |
| Manganese (Mn) | 0.0% | 0.0% | 10.7% | 12.4% |
| Titanium (Ti) | 0.0% | 0.0% | 0.0% | 9.8% |
| Graphite (C) | 16.5% | 15.3% | 16.3% | 0.0% |
| Carbon | 2.4% | 2.1% | 2.3% | 4.5% |
| Binder | 3.8% | 3.4% | 3.7% | 4.5% |
| Copper parts | 13.3% | 13.8% | 13.5% | 2.6% |
| Aluminum parts | 12.7% | 13.3% | 12.5% | 13.7% |
| Aluminum casing | 8.9% | 9.4% | 9.2% | 8.8% |
| Electrolyte solvent | 11.7% | 14.2% | 11.8% | 13.4% |
| Plastics | 4.2% | 4.6% | 4.5% | 3.6% |
| Steel | 0.1% | 0.1% | 0.1% | 0.1% |
| Thermal insulation | 1.2% | 1.3% | 1.2% | 1.2% |
| Electronic parts | 0.3% | 0.3% | 0.4% | 0.2% |

*Figure 10 Material composition of selected li-ion battery systems (Gaines, Sullivan, Burnham, & Belharouak, 2011)*

The most essential battery raw materials are cobalt, lithium, nickel and graphite (European Commission, 2018). The sourcing of these four essential battery raw materials is very concentrated in only few countries. Lithium-ion batteries contain materials that are either considered as critical or are among the candidates classified as critical raw materials (CRMs), determined in an assessment by the European Commission (European Commission, 2017b). CRMs are raw materials of a high importance to the economy of the EU and whose supply is associated with a high risk. Natural graphite and cobalt are considered as critical raw materials (CRM), while nickel, lithium and aluminium are among the candidate materials.

### 3.2.3. Battery lifetime

The degradation rate of lithium-ion batteries depends on the current state of life and therefore is a non-linear process with respect to time and stress cycles. Battery aging tests have shown that in cycling tests the degradation rate is significantly higher during the early cycles than during the later cycles, and then increases rapidly when reaching the end of life (Xu, Ulbig, Oudalov, Andersson, & Kirschen, 2016). The ageing process is dependent both on the number of charging cycles, i.e. how much the battery is used, and on calendar time (Nordelöf, Messagie, Tillman, Söderman, & Van Mierlo, 2014). Furthermore, there are several complex and interacting mechanisms relating to cell chemistry combined with storage and charging and discharging conditions such as temperature, cycle depth, discharge rate and different forms of chemical degradation that influence the battery life.

The lifetime of the battery depends on several parameters, of which one is the cycle between charging and discharging. A discharge/charge cycle is commonly understood as the full discharge of a charged battery with subsequent recharge, but this is not always the case (Battery University, 2019). In vehicles, the full capacity of a battery pack is normally not utilized, in order to extend the lifetime of the battery. The usable capacity of the battery packs is around 90% of the total capacity. When 100% SOC is displayed in the vehicle, i.e. fully charged, this could typically correspond to the single cells being charged to about 90% of the upper SOC limit given by the manufacturer. Generally, the cycle life increases rapidly when the state of charge (SOC) window, within which the cell is cycled, becomes narrower. The difference between the maximal and the minimal SOC value that is allowed, is called the SOC window and is illustrated in figure 11. To maintain the life time of the battery, the SOC window should be kept as narrow as possible. The exact size of the SOC window is hard to decide and varies between types of batteries. Marra, et al. (2012) identified a preferable SOC usage window for LFP batteries. Considering that for lifetime reasons a minimum SOC level of 20% is recommended, they state that a SOC window of 20–90% is suitable for LFP batteries. SOC and DOD are two terms that are related to each other. The State of Charge is the percentage of the capacity that is still available in the battery. Conversely, Depth of Discharge indicates the percentage of the battery that has been discharged relative to its overall capacity. A DOD of 100% would mean that the battery has discharged its full capacity. Omar et al. (2014) investigated the aging of lithium-ion batteries based on different DODs, current rates and working temperatures. The results reveal that the lower DOD, the longer the cycle life of the battery. The average SOC level has also a huge impact on the ageing, where a higher degradation rate is generally expected at high SOC level and a lower rate at lower SOC levels (Xu, Ulbig, Oudalov, Andersson, & Kirschen, 2016). High SOC levels have been detrimental for calendar and cyclic life. Higher C-rates in the lower SOC levels even generate less ageing than the lower C-rates in the higher SOC levels. Thus, avoiding high SOC can prolong the lifetime by limiting the effects from the calendar ageing. Figure 12 shows that with a SOC window of 50%, the SOC range 75-25% results in a longer expected battery lifetime than the range 100-50%. Given a window of 60%, a longer cycle life is also observed with the SOC range 85-25%, compared to the range 100-40%. These results show that higher SOC levels cause a shorter cycle life. Furthermore, the cycle life of a battery is strongly dependent on the applied charging current rate (Omar, et al., 2014). The cycle life degrades the more the charge current rate increases. Fast charging is therefore not tolerated by all lithium-ion chemistries, as it typically affects the battery functionality and accelerates its aging mechanisms. High power optimized battery cells can still absorb considerably high currents.

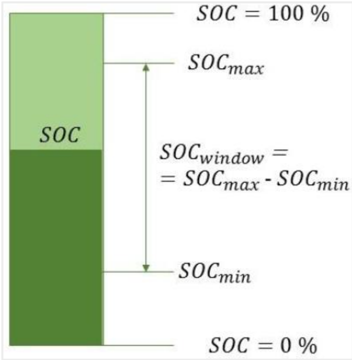



*Figure 11 State of charge*

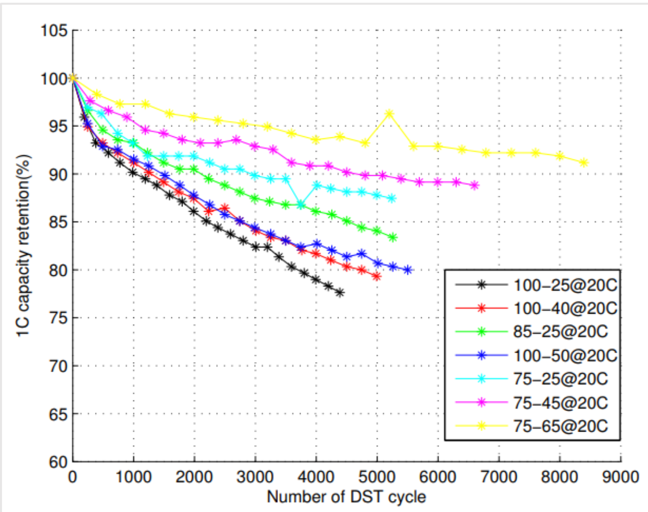



*Figure 12 Capacity loss as a function of different SOC windows (Xu, Ulbig, Oudalov, Andersson, & Kirschen, 2016)*

### 3.2.4. End of life treatment of EV batteries

Understanding the right path for batteries at their end of life is complex given the many options available as well as the rapid technology trajectory of lithium-ion batteries. These options include reuse in the original application, cascaded use in other applications, remanufacturing, recycling and ultimately disposal. Collection rates of waste batteries depend on the battery technology/type, on the lifetime of batteries, and on the end-use behavior. Achieving high levels of battery recycling can support the supply of materials for the battery value chain (Steen et al., 2017). Studies have found resource savings from recycling as well as the potential to greatly reduce the impact of EVs (Ahmadi, Yip, Fowler, Young, & Fraser, 2014). Large-scale recycling of EV batteries is not expected before 2020 and should only be more effective beyond 2025 (European Commission, 2018).

The recycling process of lithium-ion batteries is very complex, particularly when compared to that of lead acid batteries. EV batteries come in a variety of structures and cathode compositions, which means that the costs to recycle these batteries are generally high. Alexandru et al. (2015) analyzed the current industrial processes of recycling lithium-ion batteries and showed that these recycling processes are needlessly energy intensive, complicated and wasteful and do not recover an adequate amount to meet forecast demand from automotive lithium-ion manufacturers. The majority of EV batteries that have entered the market in recent years have not yet reached their end-of-life. Due to long battery lifetimes and multiple end uses, recycling is unlikely to provide significant short-term supply (Olivetti, Ceder, Gaustad, & Fu, 2017). A lot of literature is available about the recycling of batteries, covering a wide range of technologies. Industry infrastructure has progressed as well, with some companies recycling lithium-ion batteries on a commercial scale. In these instances, however, lithium is either not recovered or is recovered with impurities that make it undesirable for reuse in battery production. Due to high costs of recycling relative to the primary production and the low and volatile price of lithium, recovery and recycling of lithium from lithium-ion batteries is almost non-existent. Currently, the material of most interest to Li-ion battery recyclers is cobalt. Recycling of cobalt mainly occurs thanks to the lower costs of the recovered cobalt compared to cobalt extraction from ores. Specifically in the EV batteries sphere the recycling potential is significant as these batteries may be easier to collect if a dedicated system of return is established. Recycling of graphite, on the other hand, is quite limited. In the recycling process of batteries, graphite is usually lost in the recovery processes (European Commission, 2018).

Lithium-ion battery recycling industry is not yet adequately developed to meet the expected volumes in years to come (Drabik & Rizos, 2018). In the year 2025, 27% of these batteries will have a second-life in stationary storage units, while the remaining 73% would be available to be recycled (Curry, 2017). However, this will depend on a number of factors, including the cost to remanufacture EV batteries for storage applications, the value of materials that could be extracted from lithium-ion batteries and recycling costs (Drabik & Rizos, 2018).

### 3.2.5. Second life: stationary storage

The remaining life that EV batteries hold has inspired research looking at secondary or cascaded reuse of these batteries in other applications, such as stationary power and grid load leveling. Several studies show that repurposed batteries could be used in storage applications, including electric supply, ancillary services, grid system, and renewable integration. Energy storage refers to the storage of electrical energy through conversion to other forms of energy. A lithium-ion battery (LIB) storage system typically includes the battery itself (battery cells assembled to modules and optional pack configurations), a thermal concept or Thermal Management System (TMS) as well as an Energy Management System (EMS) control (Hesse, Schimpe, Kucevic, & Jossen I., 2017).

The need of grid-connected electricity energy storage system (ESS) continues to grow due to the furthering penetration of renewables and the increasing demand for a stable grid. The increasing use of electric vehicles in the cities increases the demand for electricity and hence exercises load on the grid. EV batteries at their end-of-life no longer meet the power requirements for a vehicle, but do retain significant storage capacity that can be used in supporting electricity grid operations. The batteries are still able to cope with charge and discharge for other applications such as electricity storage. Energy storage technologies can increase the flexibility of grid operations by providing energy buffering capacity and new ways to control the flow of energy (Ahmadi, Yip, Fowler, Young, & Fraser, 2014). Given that EV batteries still have approximately 80% of their power capacity after use for transportation, it may be feasible to repurpose them for use in energy storage and peak shifting. The peaks in demand can be equalized with peak shaving strategies. A stationary battery can for example buffer energy when no bus is charged and supply this energy afterwards in the charging process. Another advantage of peak shaving is that the grid connection costs for the bus operator could be reduced, because the operator has to pay a monthly fee for the installed power capability regardless of using time. The optimal configuration for a peak shaving system can be determined by life-cycle-cost calculations taking the invest costs for the grid connection, the stationary storage and the monthly fee for the grid connection and consumed electricity into account (Rogge, Wollny, & Uwe Sauer, 2015). The benefits of repurposing EV batteries for use in energy storage include cost savings for the end user, more effective use of the transmission grid, emissions reduction and integration of renewable power (Walker, Young, & Fowler, 2015). Emissions reduction can be achieved by allowing energy generated from renewable sources to be stored and then used instead of natural gas when demand peaks. Ahmadi et al. (2014) shows that the environmental benefits of vehicle electrification could be doubled by extending the life of EV batteries, and better using off-peak low-cost clean electricity power. The second-use of an EV battery for energy storage and load levelling would furthermore support the smart grid. Energy storage systems are seen as critical to the development of the smart grid because they can provide load shifting and peak shaving from low electrical demand periods to peak electrical demand periods, thus helping to match supply and demand variability and potentially allowing for cost savings for energy providers and consumers.

# 4. Methodology

*This chapter describes the research methodology and introduces the case that is being used in the research. First, the methodology is being discussed including the method, goal, scope, and limitations. After, the case including the scenarios to be compared with each other are presented.*

## 4.1. Methodology

First, this section explains the method being used for the sustainability assessment of the supply chain of the electric bus transportation. Thereafter, the goal, the system boundary and the limitations of this study are being discussed.

### 4.1.1. Method

The thesis aims to assess the environmental and economic sustainability of the battery bus operation based on the most applied charging strategies in the Netherlands. IO modeling is being applied to the scenarios to compute the material, energy and waste flows of the supply chain. In order to do that, first a physical and after a monetary enterprise input-output table is being created. The physical EIO model serves as a planning tool while the monetary EIO model serves as an accounting tool for the supply chain actors. The rationale of computing first the physical flows is to be able to calculate the technical coefficients among supply chain processes. Then, coefficient matrices are being multiplied by unit price vectors to create the monetary input-output tables. This serves as an accounting tool for measuring economic sustainability. For each scenario, we compute the economic and environmental performance indicators and discuss the results comparatively. For that purpose, $CO_2$ emission serves as the environmental sustainability indicator while total costs serve as the economic sustainability indicator. The index used for the assessment of the $CO_2$ emissions in this study is the emission of carbon dioxide as equivalent to the energy production for each battery.

### 4.1.2. Goal

The goal of this study is to assess the environmental and economic sustainability of the battery buses in the scenarios via enterprise input-output modeling. Through a case example, this thesis aims at identifying the most sustainable charging scenario using the sustainability indicators: $CO_2$ emission and total costs. The case being used is bus line Y. The choice for this line has been made due to availability of data and the line's suitability for all charging strategies. In other words, all charging scenarios can be applied on this bus line.

### 4.1.3. Scope

The battery is the most important component of an EV since it characterizes the vehicle under several points of view: energy and power capacity, range, weight, cost and lifetime. Therefore, the focus of the research is on batteries. The thesis does not cover all life cycle stages of bus transportation. The production of the bus and its components other than batteries and the end of life treatment are left out of consideration. Given the recent introduction of EVs on the European market, and taking into account the average lifetime of EV batteries, a significant number of EVs have not yet reached end-of-life. Hence, there is a limited amount of information on the end of life treatment of EV batteries. Furthermore, the intrinsic value of the key metals in LFP cells is the lowest of all the major EV batteries currently on the market, which translates to less value per kg of recycled material. The reduced valuable material in battery chemistries combined with high recycling costs makes recycling unattractive, which is why it is not considered in the analysis. The included processes are the raw material extraction and processing to usable form, battery production, charging and bus operation. The complete production chain of the batteries is aggregated in the 'battery production' process. Due to time restrictions and limited data availability, only certain battery materials and byproducts in the supply chain of bus transportation is being considered. Within this case study, we look at three key materials used in $LiFePO_4$ batteries: lithium, aluminium ,and graphite. Lithium is not a CRM, but has increasing relevance for the Li-ion battery industry. It is expected that lithium will experience increased demand in line with the expected growth in demand for EVs. Aluminium has been selected on the basis that it is used in high quantities in the casing of the battery pack. The amount of aluminium, compared to other materials in the battery pack, is substantial (see Section 3.2.2.). As such, the growth in the EV market will likely mean an increase in demand for aluminium. Graphite is another key component of lithium-ion batteries and is used in the anode of the battery. Natural graphite has been identified by the European Commission as a critical raw material and is both of high economic importance for the EU and is vulnerable to supply disruptions. Materials other than these key metals are not taken into account. Furthermore, the air pollutants as $NO_x$, $SO_2$ and PM created by the processes are not considered in the analysis.

#### 4.1.4. Limitations

The most important limitation of this research is the availability of data. There is uncertainty with regard to the production of lithium-ion batteries. As the battery technology market is expanding, new batteries with different chemistries become available. Hence, data concerning the production of particular lithium-ion batteries are either unavailable, scattered or of low quality. Especially, reliable data regarding the production of lithium iron phosphate batteries is limited. Furthermore, some key figures are used for the calculation of the investment costs. The construction of the charging and electric infrastructure is customized, making it difficult to assess generic costs. Therefore, the investment costs in the calculations don't cover all the costs that have to be made for the implementation of a charging scenario. The costs of the particular units used for the calculations are based on the expertise of Company X and are given in Appendix E. There is also a limited amount of information on the recycling of EV batteries, as currently, very few batteries have reached their end-of-life. It is not possible to gather information on the costs of collection, dismantling, recycling and repurposing EV batteries as a storage application through the desk-based research or through the interviews conducted. Data with regard to the use of the batteries as energy storage is either not available, confidential or of low quality. Uncertainty about raw material prices and technological advancements is also a key limitation of the study. Raw material prices are experiencing significant volatility, which affects the battery price. With technological advancements in the recycling sector, the technical and/or economic feasibility of recycling EV batteries and recovering particular materials within those batteries may change. It may also change the feasibility of battery cells enduring a second-life within a storage application. On the other hand, business models may evolve and develop a market for reusing battery cells from EVs that make it more economical than direct recycling.

### 4.2. Presentation of the case

This section presents the relevant boundary conditions for the analysis. The first part describes the considered bus line consisting of a certain set of service trips per day, which are currently operated with conventional diesel buses. The second part presents the scenarios that are being analyzed in this research. The scenarios are based on the most common charging strategies that are being applied in the Netherlands. There are currently two common charging strategies of the zero-emission bus transport: overnight charging and a mix of opportunity and overnight charging. Elaad (2017) performed a market research in which they determined the expected number of applications for different charging scenarios in the Netherlands. According to this research, the combination of overnight and opportunity charging will likely be the most applied charging strategy in the country. Hence, this research aims to understand the differences between overnight charging, opportunity charging and the combination of both charging strategies. Each scenario processes one charging strategy, resulting in the analysis of three scenarios. Based on the implementation of a charging strategy, this research aims to analyze the sustainability of the bus transportation supply chain.

#### 4.2.1. Bus line Y – Station Z

Station Z is a railway station in the Netherlands. There is a bus station in front of the station, consisting of four platforms, where several bus lines have their start and end stops. Currently, there are four local bus lines and ten regional bus lines operating from and to the station.

The charging scenarios are being analyzed in the specific case of bus line Y, whose route starts and ends in station Z. The total distance of the route is equal to 10.1 km. The bus transportation has not been electrified yet as the buses are driving on fossil fuel, however there is a preparation to introduce electric buses for this bus line. Company X is currently investigating the electrification options for the whole concession and therefore the bus technology, including the battery type and size, and the charging infrastructure that will be used are not definite. The exact locations of the depot and the charging stations are also uncertain, nevertheless Company X has expectations about the location of the depot and the required charging infrastructure. The distance between the depot and the bus station is 8.2 km with a ride time of 16 minutes. In the current operating schedule, 60 service trips are carried out per workday, starting and ending in the bus station. Furthermore, 48 and 32 rides are offered on Saturdays and Sundays respectively. The electric bus transportation will be adapted to the current timetable. In the beginning, the electric buses will be powered by electricity from the grid, so that the electric energy comes from fossil fuels. Ultimately in 2030, it is the intention to supply the buses with 100% locally generated renewable energy (solar energy).

#### 4.2.2. Actors in the supply chain

Four important actors can be identified in the supply chain of electric bus transportation belonging to the case: the battery manufacturer, the provider of the charging infrastructure and the bus operator. The charging infrastructure is supplied in accordance with the specifications of the bus manufacturer and the wishes of the concession holder to be placed at the depot and/or bus station. The concession holder is the bus operator on a concession and is the party that has most of the influence on the concrete implementation of ZE public bus transport. It is the bus operator's responsibility to come up with a proposal with a mix of quality, affordability and sustainability at the lowest possible price. However there are more stakeholders involved that are not immediately seen in the picture. These stakeholders are involved in the electricity production and transmission, which are managed by the energy provider and the grid operator respectively.

#### 4.2.3. Scenario I: Overnight charging

In this scenario, the buses are only charged in the depot using the plug-in technique. The charging takes place only at night, which means that the batteries should have enough capacity to cover the energy demand during the day. The energy supply during the week and the weekend is not the same due to unequal number of rides that are done. The necessary infrastructure for charging of the buses consist of the slow chargers which charge the buses in approximately 6 hours per day. The buses are (dis)connected to the grid manually before/after bus operation by the bus driver. Figure 13 presents the main production processes in the battery bus transportation for scenario I. The first process is the battery production, where battery is being produced and implemented in the bus and is fully charged. Then, the bus operation takes place and at the end of the operation the bus returns with a partially discharged battery to the depot, where it is fully charged. The next day, the buses start service with a fully charged battery pack and operate whole day without recharging. These processes continue till the battery reaches 80% of its original capacity and thereby cannot be used in the buses anymore. This is when the batteries reach their end of life.

The scenario consists of four processes: battery production, bus operation, overnight charging and bus operation. Battery production comprises the inputs and outputs during the manufacturing of the battery, while the bus operation refers to the energy consumption during driving the buses. There are two bus operation processes in the supply chain. The first one refers to the first operation day, so that input of this process is a fully charged battery that comes from the production phase. The input of the second bus operation process is a battery that has been fully charged overnight after bus operation was finished. The charging process represents the well-to-tank (WTT) stage of the life cycle of electric bus transportation and thereby refers to any impacts from electricity production occurring upstream of vehicle charging. The 'overnight charging' process in the supply chain aggregates the following processes: the generation and transmission of electricity and the charging of the batteries.

As it is also given in figure 14, the battery is the main input and output of all processes in the supply chain. The batteries only differ in the percentage of available capacity with respect to the maximum battery capacity. The primary inputs are aluminium, lithium, graphite, workforce and electricity and $CO_2$ is the only byproduct in the supply chain. The workforce refers to the operating hours and depends on the number of bus drivers and therefore on the number of buses. The $CO_2$ emission can be attributed to the energy use during the battery production and overnight charging processes.

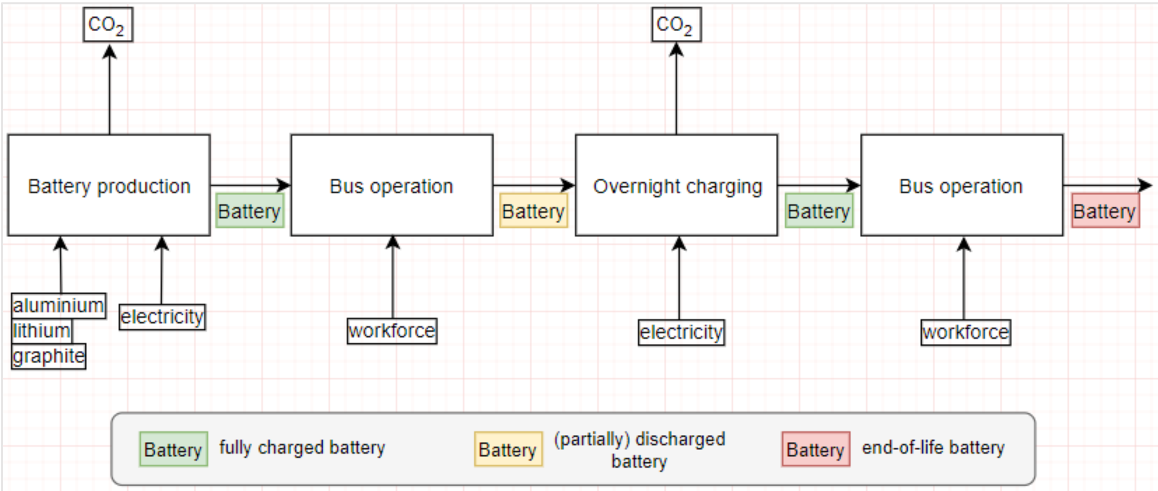



*Figure 14 Scenario I: Overnight charging*

### 4.2.4. Scenario II: Overnight and opportunity charging

Scenario II combines opportunity charging and overnight charging. This means that the buses are slowly charged at night using a plug (as it is the case with scenario I) and recharged during the day at higher power using a pantograph. The buses are ideally recharged during the dwell time. While overnight charging takes place at the depot, opportunity charging takes place at the bus station. Figure 15 visualizes scenario II in which a mix of both charging strategies is applied. The supply chain of scenario I and II are very much alike, however the supply chain of scenario II includes the process 'bus operation and recharging' instead of the process 'bus operation' (scenario I). The 'bus operation and recharging' process refers to the energy consumption of the bus during the day and hence includes the amount of energy supply during recharging. The workforce is the input to bus operation while electricity is the input to recharging. Additional charging and electric infrastructure is needed at the bus station for charging of the buses during the day. Slow chargers and plugs are required at the depot, while a fast charger and a pantograph is used at the station. Buses can manually be connected to the charging points by the bus driver in both charging techniques, so that no additional workforce is needed during (re)charging.

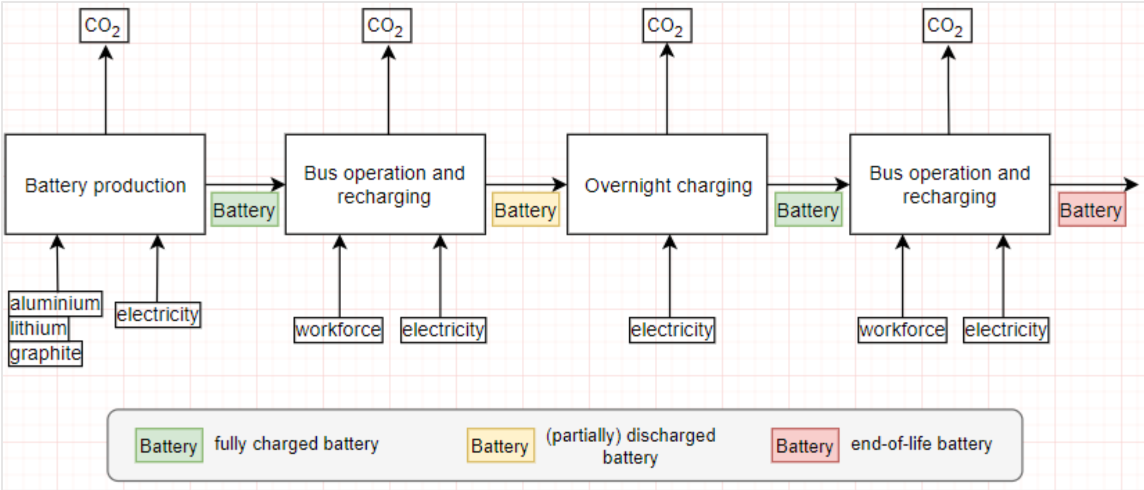



*Figure 11 Scenario II: Overnight and opportunity charging*

### 4.2.5. Scenario III: Opportunity charging

Opportunity charging refers to charging during bus operation. In this scenario, buses are recharged during halting time and after operation is finished. Charging only takes place at the bus station and hence electric and charging infrastructure is only needed at the station. After the last ride of the day, the buses arrive at the bus station where they fully charge the batteries and then drive to the depot. Fast charging is used to make sure that batteries are charged in time, given the available halting time. The supply chain of opportunity charging is given in figure 16. The current scenario only makes use of recharging at the bus station during the day, which is represented by the 'bus operation and recharging' process in the supply chain. It can be observed that the main output of the 'charging' process is a partially discharged battery. This indicates that the buses start the next operation day with a partially discharged battery, as the battery capacity decreases due to travel from and to depot.

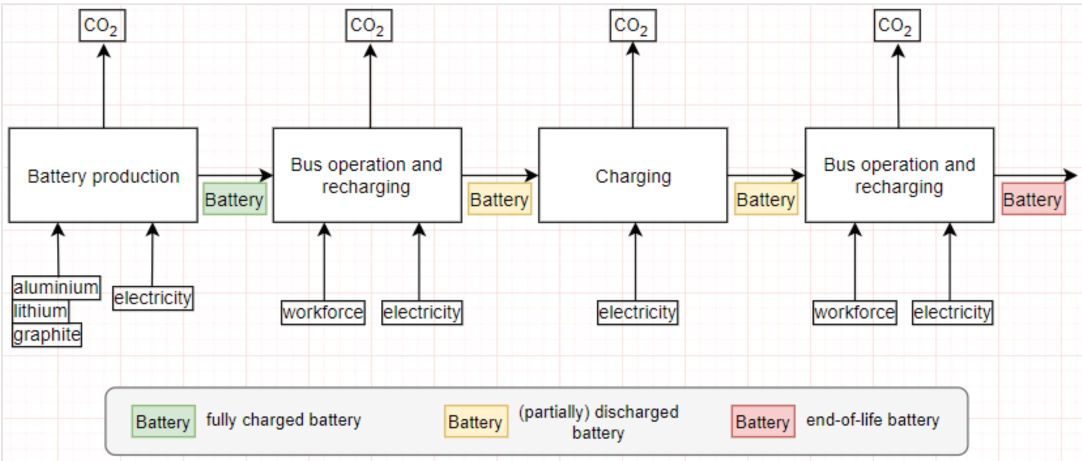



*Figure 16 Supply chain diagram of scenario III*

# 5. Assumptions

*This chapter highlights the processed raw data and thereby the assumptions of the study. The first part describes the general assumptions made with regard to the battery choice, battery life and energy consumption of the buses. Furthermore, the charging strategy in the scenarios is being explained. The second part presents the scenario characteristics in terms of number of trips, energy consumption and charging profile.*

## 5.1. General assumptions

This section presents the assumptions of the case. First, the section explains the battery choice for each scenario and how an approximation of the battery life is being done. Thereafter, the assumptions made with respect to the energy consumption of the buses and the applied charging strategy per scenario is being presented.

### 5.1.1. Battery composition

The charging scenarios that are compared with each other allows us to distinguish two types of buses: plug-in buses and opportunity charging (OC) buses. The plug-in buses are only charged overnight using a plug, while the OC buses can also be charged during the day at the bus station using a pantograph up system. It is assumed that all buses are equipped with the same technology, components and battery type. The only difference between the buses is the battery size and therefore the weight of the buses. Larger batteries are assumed for the plug-in buses to complete their trips during the day without the need to recharge. Larger batteries reduce the passenger capacity of the buses, hence possibly requiring the use of more buses. However, in this study it is assumed that all buses have the same passenger capacity. The battery size of the buses is mainly determined by range. The range indicates the total kilometers the vehicles drive per day, including the distance from and to the depot. When choosing the battery size, it is also taken into account that the buses arrive at the depot at the end of the day with at least 20% SOC. The plug-in buses are supplied with a battery package of 500 kWh. The OC buses can recharge during the day and therefore have smaller batteries compared to plug-in buses. The OC buses for scenario II and III have a battery capacity of 200 kWh and 79 kWh respectively.

It is assumed that all buses are supplied with lithium iron phosphate ($LiFePO_4$) battery cells. $LiFePO_4$ is currently the most common battery type used by the European bus manufacturers (ZeEUS, 2017). In general, the study lacked cooperation with a battery manufacturer to provide data on battery manufacturing. Therefore, it was necessary to make rough assumptions and approximations about the production of $LiFePO_4$ batteries based on literature and the following tools: ecoinvent database, LCA software SimaPro and LCIA: the ReCipe model. The data source for the life cycle inventory is the ecoinvent database, which is incorporated in SimaPro to calculate the production impact of the batteries. The material and electricity use for battery production is calculated through the whole production chain and given in Appendix E.

### 5.1.2. Battery life

In this study, it is assumed that all buses are only used for bus line Y and according to bus schedule given in Appendix C throughout the lifetime of the bus. As it is explained in chapter three, there are many factors that influence the battery life, including environmental factors (temperature and humidity), battery chemistry and charging conditions (depth of discharge and current rate). Furthermore, the battery life is dependent on the manufacturer and the product quality.

The service life of a battery is specified in number of cycles, as the number of charge cycles affects life more than the mere passage of time. Battery manufacturers often specify the cycle life of a battery with a 80% DOD. Evaluating battery life on counting cycles is not conclusive, because a discharge may vary in depth and there are no clearly defined standards of what constitutes a cycle. Therefore, cycle life is estimated for specific charge and discharge conditions. Appendix D presents figures that estimate the number of cycles for $LiFePO_4$ battery cells according to the discharge power and DOD figures. The actual operating life of the battery is affected by the rate and depth of cycle. The higher the depth of discharge, the shorter the cycle life. Figure 47 in the Appendix shows that a shorter cycle life is also expected with a higher C-rate, with the impact being bigger as you reach lower DOD (left in the figure).

It is complicated and time consuming to come up with an accurate estimate of the battery life, due to many factors that influence the battery life. Considering the time available and the scope of this research, we only consider the DOD, which is one of the factors that has the largest impact on the battery lifetime, and disregard the factors other than that. For that purpose, we use data from battery manufacturers and literature. Appendix D presents the figures that show the cycle life given a discharge current rate of 1C. Based on these figures, an average lifetime for the batteries in the scenarios is determined. The rounded DOD values, the expected number of cycles before reaching 80% of original capacity and thereby the expected lifetime of the batteries are given in table 2. The table shows the expected lifetime for each bus in a particular scenario. It can be observed that for the buses 1 and 2 in scenario I a life time of 10.4 years is approximated.

| SCENARIO | DEPTH OF DISCHARGE (%) | EXPECTED CYCLE LIFE | EXPECTED LIFE TIME (YEARS) |
|---|---|---|---|
| **SCENARIO I** | 70% | 3800 | 10.4 (Bus 1,2)<br>12.2 (Bus 3) |
| **SCENARIO II** | 40% | 9250 | 13.2 (Bus 1)<br>13.7 (Bus 2)<br>21.0 (Bus 3) |
| **SCENARIO III** | 30% | 15833 | 11.3 (Bus 1)<br>11.7 (Bus 2)<br>17.9 (Bus 3) |

*Table 2 Battery lifetime in the scenarios*

### 5.1.3. Energy consumption

The energy consumption of the buses depends on many factors as explained in section 3.1.3. and differs per bus manufacturer, as every manufacturer uses different components, materials, battery type and thereby delivers a different bus. The bus composition has an influence on the weight of the bus and its speed which in turn affects the consumption. Since the composition of the buses in the scenarios are the same, except for their battery size, the consumption in the scenarios is based on the battery size. In this study, the energy consumption of all buses is derived from 1) expertise of Company X and 2) TNO report (2015) and include the factors that affect the consumption such as the driving resistance and the use of auxiliaries. It is assumed that the energy consumption remains the same throughout the year and is not influenced by the topography (mainly flat), road quality and the driving style of the bus driver. During a cold winter day the consumption could be higher, and hence it is assumed that at very low temperatures bio-heaters are used. The most important parameters in the scenarios are summarized in table 3. The amount of energy needed onboard is more than the total energy being supplied to the battery, which is due to the efficiency of the infrastructure components and the charging units. The efficiency of the particular components are incorporated in the calculations and given in Appendix E.

| SCENARIO | TYPE OF BUS | BATTERY SIZE [KWH] | ENERGY CONSUMPTION [KWH/KM] | (RE)CHARGING | NUMBER OF BUSES |
|---|---|---|---|---|---|
| **SCENARIO I** | Plug-in | 500 | 1.6 | Depot | 3 |
| **SCENARIO II** | OC bus | 200 | 1.4 | Depot, Bus station | 3 |
| **SCENARIO III** | OC bus | 79 | 1.1 | Bus station | 3 |

*Table 3 Summary of parameters for the scenarios*

### 5.1.4. Charging strategy

Overnight charging only happens at night at the depot and opportunity charging is done during dwell time at the bus station. The dwell time is equal to the time between arrival at the bus station and the departure time for the next ride. Theoretically, 100% utilization of the battery capacity would require the cell to be charged at very low rates for a very long time. Usually, the batteries are not 100% utilized. When 100% SOC is displayed in the vehicle, this could typically correspond to the single cells being charged to about 90% of the upper SOC limit given by the manufacturer. In the same way, the 0% SOC indication in the vehicle is normally not the 0% rated SOC of the battery cells. Typically, this will be around 10–20% SOC. In this study, we assume 20% SOC as the lower limit and 90% SOC as the upper limit. With these limits, the batteries can have a maximum of 70% DOD.
For each scenario a suitable SOC window is being identified based on the battery size and the total distance covered per day. For overnight charging, we assume a SOC window of 70%, with a minimum of 20% and a maximum of 90%. This means that the minimum level of charge is equal to 20% and hence the buses should arrive at the depot with at least 20% SOC, otherwise they are not suitable for the charging scenario considered. Furthermore, the batteries are considered fully charged with a SOC of 90%. This is actually a large window, but a smaller window can only be realized with a larger battery. Considering the relative size of the batteries in this scenario, a larger battery would have more disadvantages, e.g. high energy consumption. Furthermore, lower charging power is used with overnight charging to minimize the impact of the large DOD on the life time of the battery. In other words, the C-factor, which indicates the charging speed, is low enough to compensate for the large SOC window being used. The C-factor is a measure of the rate at which a battery is discharged relative to its maximum capacity. The lower the value, the better it is for the battery life. The choices between the loading capacity of the charging unit, the C-factor value and the capacity of the battery are related to each other and are shown in the formula below:

$$minimal\ battery\ capacity = \frac{charging\ power\ of\ loading\ unit}{C - factor}$$

For scenario II, we assume a SOC window between the limits 46% and 90%. This results in recharging of the buses once per six trips. Thus, the buses recharge upon arrival at the station after each sixth ride. After the last ride of the day, each bus is assumed to drive to depot and charge immediately after arriving. The available charging time is between the arrival time at the depot and sixteen minutes before the first ride of the next day. Sixteen minutes refers to the travel time between the depot and the bus station. This means that the buses can charge during their total stay at the depot. The SOC window for scenario III is defined as 61%-90%, requiring the buses to recharge once every two trips. These buses, however, only charge at the station. As soon as the last ride of the day is finished, the buses fully charge the batteries at the station and then drive to the depot.

### 5.2. Assumptions per scenario

This section presents the assumptions per scenario. The number of service trips is identified for each scenario and subsequently used in the energy consumption calculation. Based on this information, the charging profile for the buses during the week and the weekend is calculated. The maximum charging power of the charging units are chosen such that they provide sufficient power to charge the batteries in the available (halting) time.

#### 5.2.1. Scenario I: Overnight charging

In this study, we use the current timetable of the bus line and assume that the zero-emission bus transport needs to be adapted to this schedule. We assume that the buses don't switch routes, so that all buses need to store enough energy to drive the route of bus line Y. The scheduling of the rides, that minimizes the number of buses used while taking into account the SOC window, results in three buses that make an equal number of trips every workday. The number of rides per bus during the week is given in table 4. The distribution of the rides has been done in such a way that minimum number of buses is being used and the battery capacity is kept as small as possible, taking into account the SOC window that applies to this scenario. All buses have the same number of rides in scenario I, because more trips per bus requires a larger battery size to store the energy needed to complete the rides.

| day | # of required buses | # of rides per bus | | |
|---|---|---|---|---|
| | | Bus 1 | Bus 2 | Bus 3 |
| **Workday** | 3 | 20 | 20 | 20 |
| **Saturday** | 3 | 16 | 16 | 16 |
| **Sunday** | 2 | 16 | 16 | |

*Table 4 Number of rides per bus per day for scenario I*

Together with the drive from and to the depot, the total distance covered per day is equal to 218.4 km per bus. Given an energy consumption of 1.6 kWh/km, the energy supply needed onboard is equal to 349.4 kWh. This means that the batteries need to have a capacity of 500 kWh, assuming a SOC window of 70%. The losses during the transfer of electricity from the grid to the charging unit and from the charging unit to the battery are given in Appendix E. The total energy use for scenario I is calculated to be 396.2 kWh including the losses, which results in 257.1 kg $CO_2$ emission per day per bus. For all buses the time that is available for charging at the depot is approximately 7 hours. Given the battery capacity of the buses and the available charging time before operation, the maximum load capacity of the charging station is 60 kW. This corresponds to a C-rate of 0.12, which implies that the battery would be 100% charged in 8.3 hours. However, we only need the bus to be charged in cycles of 70% (of the total battery capacity), so that 5.8 hours of charging is enough for the daily operation. The most relevant information of scenario I is summarized in table 5. The table shows the distance travelled and the energy supply in a certain day of the week. The first row presents the amount of energy consumed by a bus operating during a working day, while the second row presents the consumption of a bus during the weekend.

| | Distance travelled per day [km] | Total energy consumption per day [kWh] | Total energy supply per day [kWh] | $CO_2$ emission per day [kg$CO_2$/kWh] |
|---|---|---|---|---|
| **Workday** | 218.4 | 349.4 | 396.2 | 257.1 |
| **Saturday/ Sunday** | 178.0 | 284.4 | 322.9 | 210.0 |

*Table 5 Relevant information for scenario I*

Figure 17 presents the available battery capacity of the plug-in bus after each ride at the station. The graph is decreasing, since no recharging takes place during the day. It can be observed, that in the morning the buses depart with a fully charged battery from the depot and at the end of the day arrive at the depot with circa 20% remaining capacity. Less trips take place in the weekend, so that after bus operation the buses arrive at the depot with 32% SOC, which is shown in figure 18.

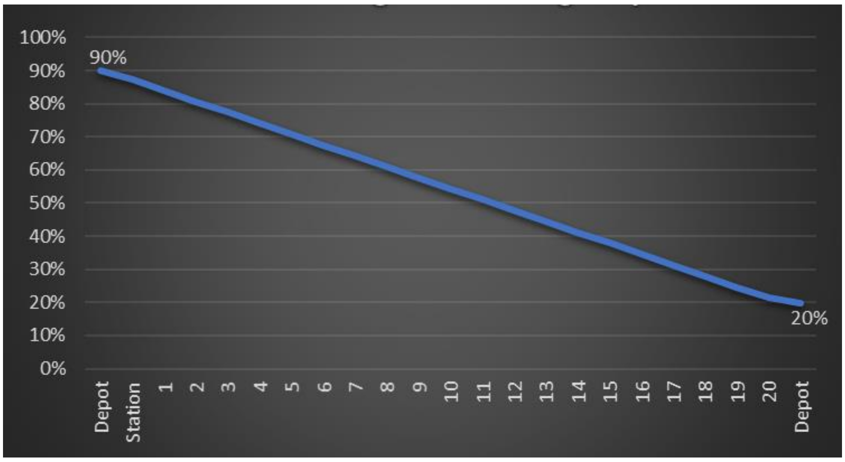



*Figure 17 State of charge during a working day for all buses in scenario I*

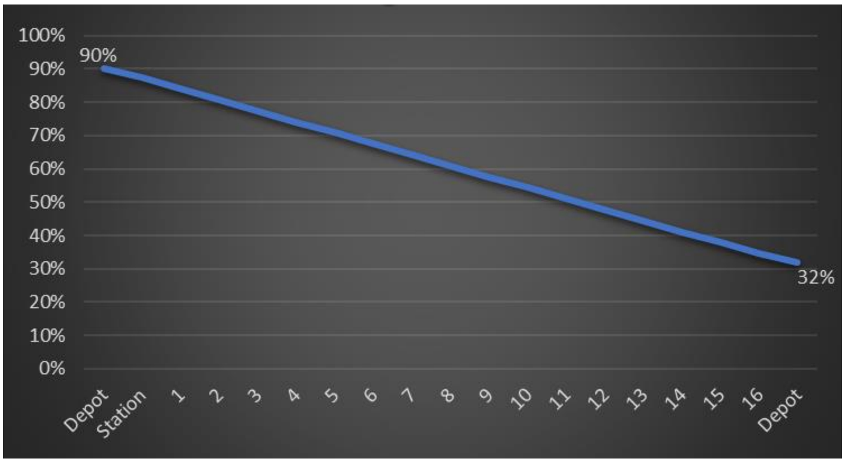



*Figure 18 State of charge during the weekend for all buses in scenario I*

### 5.2.2. Scenario II: Overnight and opportunity charging

In scenario II, charging at the depot is combined with charging at the end stop (bus station). The charging is first carried out at the depot. It is assumed that the batteries should be charged to the maximal allowed SOC level when leaving the depot in the morning. Scenario II also assumes that three buses are deployed for the daily operation. The number of rides required per bus during the week is given in table 6. The number of rides per bus are determined such that minimum working hours is needed, taking into account the SOC window which applies to this scenario.

| day | # of required buses | # of rides per bus | | |
|---|---|---|---|---|
| | | Bus 1 | Bus 2 | Bus 3 |
| **Workday** | 3 | 22 | 22 | 16 |
| **Saturday** | 3 | 22 | 16 | 10 |
| **Sunday** | 2 | 16 | 16 | |

*Table 6 Number of rides per bus per day for scenario II*

The energy consumption of the buses differs per day of the week, dependent on the number of rides. During a work day, the energy consumption is equal to 334.0 kWh (buses 1 and 2) and 249.2 kWh (bus 3). The total energy supply is 386.6 kWh (bus 1 and 2) and 288.4 kWh (bus 3), which results in 250.9 kg and 187.2 kg $CO_2$ emission per day respectively. The most relevant information per bus in scenario II is given in table 7. The table presents the energy consumption of one bus on a certain day, e.g. the first row shows the consumption of the buses 1 and 2 on a working day and bus 1 on Saturday. This means that for bus 1 the energy supply on working days and Saturdays is the same. In fact, the energy consumption depends on the number of rides done and thus is the same on the days when equal number of rides are made.

| Bus | Distance travelled per day [km] | Total energy consumption per day [kWh] | Total energy supply per day [kWh] | $CO_2$ emission per day [kg$CO_2$/kWh] |
|---|---|---|---|---|
| **Workday (Buses 1 and 2)<br>Saturday (Bus 1)** | 238.6 | 334.0 | 386.6 | 250.9 |
| **Workday (Bus 3)<br>Saturday (Bus 2)<br>Sunday (all buses)** | 178.0 | 249.2 | 288.4 | 187.2 |
| **Saturday (Bus 3)** | 117.4 | 164.4 | 190.2 | 123.5 |

*Table 7 Relevant information for scenario II*

The present battery capacity should ideally remain between 46% and 90% during operation. After finishing each sixth ride, the bus connects to the charging pole at the station to recharge. With a C-rate of 3, the bus batteries are recharged through a load unit that can provide a power of 600 kW per hour. Figure 19 presents the state of charge of bus 1 (during working days and Saturdays) and bus 2 (during working days) at the depot and after finishing a ride at the station. The figure shows that the SOC window is equal to 44%. At the end of the day, the bus has a battery capacity of 47% left upon arrival at the depot. During the stay at the depot, the batteries are charged to 90%, so that the bus operation starts the next day with a full battery capacity. Figure 20 shows the present battery capacity of bus 3 during operation in the week. It can be observed that bus 3 performs 16 rides every working day. Due to same number of rides, figure 20 applies to bus 1 on Sundays and bus 2 during the whole weekend. The state of charge on Saturdays for bus 3 is given in figure 50 in Appendix E.

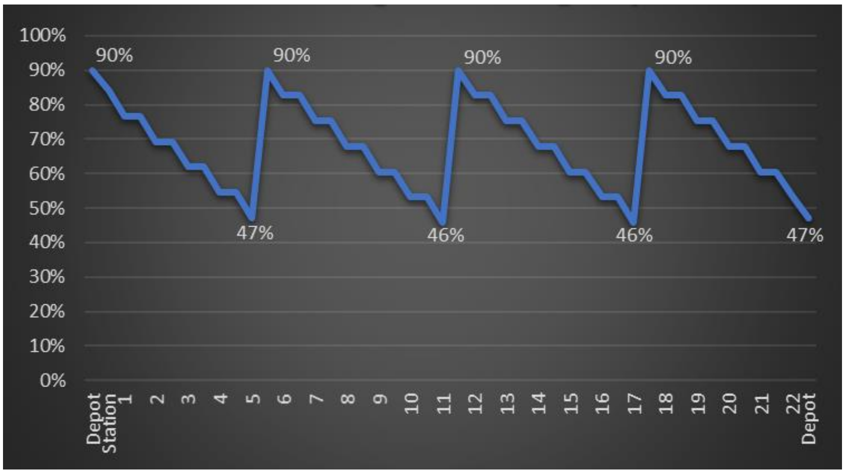



*Figure 19 State of charge during a working day for bus 1 and 2 and on Saturday for bus 1*

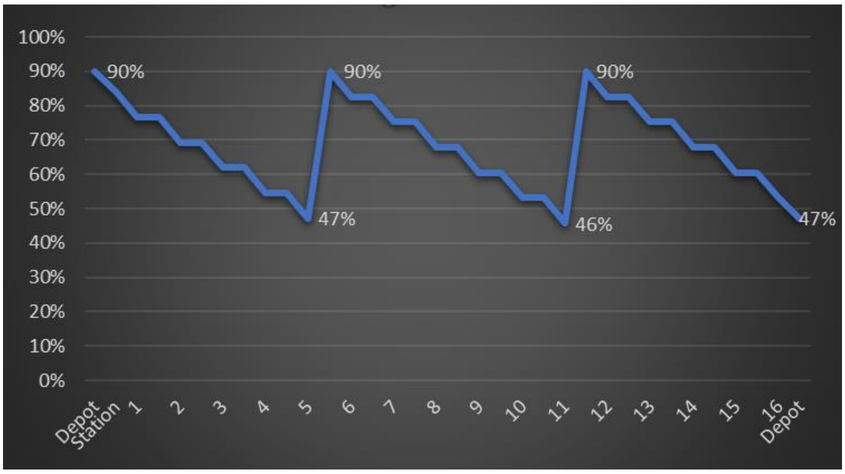



*Figure 20 State of charge during a working day for bus 3*

### 5.2.3. Scenario III: Opportunity charging

In scenario III, charging of the batteries only happens at the bus station. This means that after finishing the last ride of the day, the buses fully charge their batteries at the station before driving to depot. The number of rides required per bus during the week is given in table 8. The number of rides per bus are chosen such that minimum working hours is needed, taking into account the SOC window which applies to this scenario.

| **day** | **# of required buses** | **# of rides per bus** | | |
|---|---|---|---|---|
| | | Bus 1 | Bus 2 | Bus 3 |
| **Workday** | 3 | 22 | 22 | 16 |
| **Saturday** | 3 | 22 | 16 | 10 |
| **Sunday** | 2 | 16 | 16 | |

*Table 8 Number of rides per bus per day*

The energy consumption of the OC buses during a workday and the weekend is shown in table 9.

| | **Distance travelled per day [km]** | **Total energy consumption per day [kWh]** | **Total energy supply per day [kWh]** | **$CO_2$ emission per day [$kgCO_2/kWh$]** |
|---|---|---|---|---|
| **Workday (bus 1 and 2) Saturday (Bus 1)** | 238.6 | 262.5 | 303.8 | 197.1 |
| **Workday (Bus 3) Saturday (Bus 2) Sunday (Buses 1 and 2)** | 178.0 | 195.8 | 226.6 | 147.1 |
| **Saturday (Bus 3)** | 117.4 | 129.1 | 149.5 | 97.0 |

*Table 9 Relevant information for scenario III*

The maximum charge capacity of the charging unit is 300 kW, which corresponds to a C-rate of 3.8. The SOC of the OC buses during operation is given in figure 21 and 22. During the day, the buses recharge when the SOC drops to 61%. This causes the buses to recharge once every two rides. After finishing the 22th ride, the buses are being fully recharged for the last time before going to depot. Upon arrival at the depot, the SOC is equal to 78%.

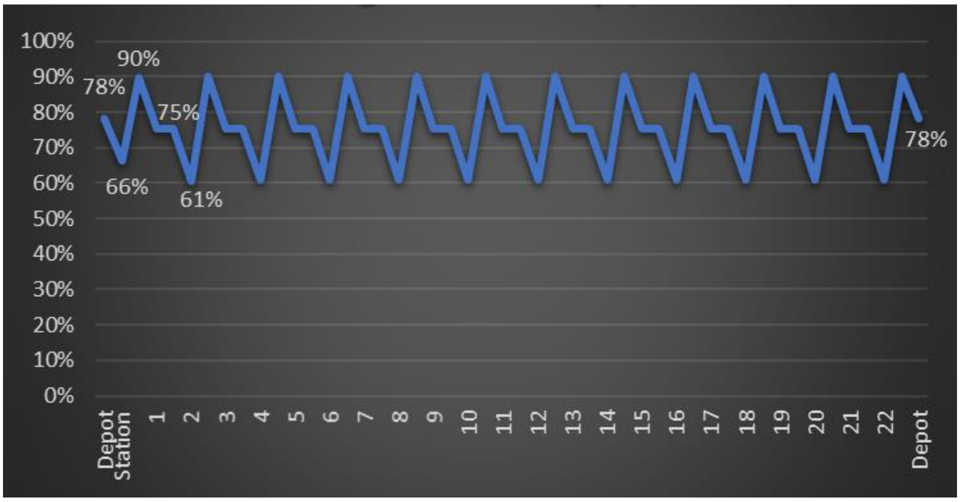



*Figure 21 State of charge when 16 rides are done in scenario III*

The SOC during the work days for buses 1 and 2 is shown in figure 21 and for bus 3 in figure 22. It can be observed that the SOC always remains between 61% and 90% for all buses. After the last ride of the day, the bus arrives with 61% present battery capacity at the station, where the battery pack is being fully recharged before driving to depot. Upon arrival at the depot, the SOC of all buses is equal to 78%, which means that the buses start the following day with a partially discharged battery. Upon arrival a at the station with a SOC equal to 66%, the batteries are fully recharged.

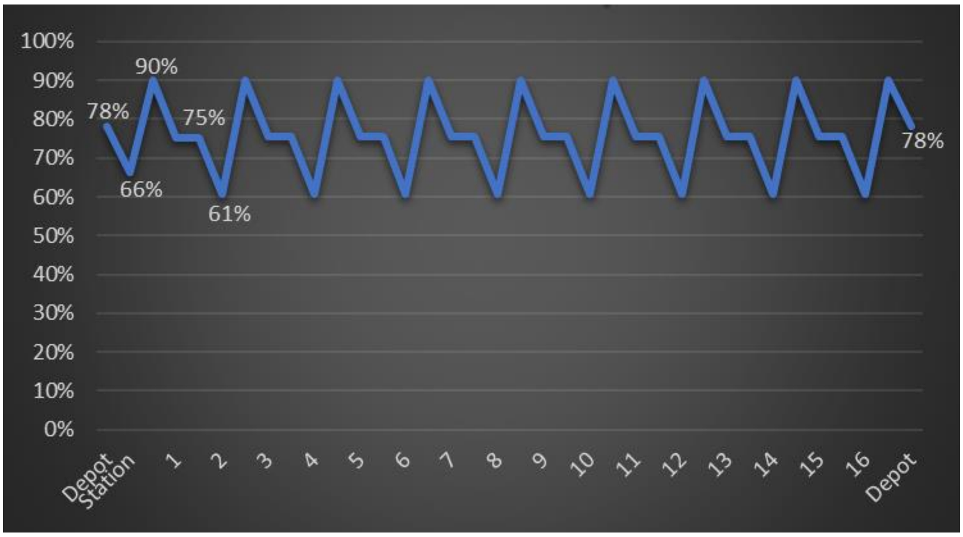



*Figure 22 State of charge during the weekend for scenario III*

Figure 22 also shows the present battery capacity during the day on Saturdays for bus 2 and on Sundays for buses 1 and 2, as the number of rides for these buses is equal these days. As the only difference is the number of rides done per bus, the average SOC level during the week is the same for all buses. The SOC window is the same for all buses, and hence the average SOC level is also the same. Figure 51 in Appendix E presents the state of charge on Saturdays for bus 3.

# 6. Results and discussion

*This chapter presents and elaborates on the results from the EIO modeling. First, physical input-output tables are used to quantify the material, energy and $CO_2$ flows for each scenario. The largest contribution to $CO_2$ is evaluated in detail. Then, the physical input-output tables are integrated to the monetary EIO model to compute the economic performance of the supply chains. The chapter ends with discussion of the monetary input-output tables.*

## 6.1. Environmental sustainability

This section presents the physical input-output tables for the scenarios. The physical input-output tables show per battery the primary input consumption and waste generation by each process in the supply chain of bus transportation. For each scenario, three physical tables are calculated, one for each bus used in the scenario. At the end of this section, all tables of a scenario are summed in one column in table 10.

| Processes | | | P1 | P2 | P3 | P4 | Final demand | Total output |
|---|---|---|---|---|---|---|---|---|
| P1 | Battery production | fully charged battery | - | 0.10 | 0 | 0 | 0 | 0.10 |
| P2 | Bus operation | partially discharged battery | 0 | - | 0.10 | 0 | 0 | 0.10 |
| P3 | Overnight charging | fully charged battery | 0 | 0 | - | 0.10 | 0 | 0.10 |
| P4 | Bus operation | end-of-life battery | 0 | 0 | 0 | - | 0.10 | 0.10 |
| **Primary inputs** | | | | | | | **Total primary input use** | |
| r1 | Aluminium | kg | 4.60 | 0 | 0 | 0 | 4.60 | |
| r2 | Lithium | kg | 0.25 | 0 | 0 | 0 | 0.25 | |
| r3 | Graphite | kg | 3.75 | 0 | 0 | 0 | 3.75 | |
| r4 | Workforce | person hour | N/A | 17 | 0 | 5911 | 5928 | |
| r5 | Electricity | kWh | 879 | 0 | 121160 | 0 | 122039 | |
| **By-products** | | | | | | | **Total by-products** | |
| w1 | CO2 | kg | 570 | 0 | 78633 | 0 | 79203 | |

*Figure 23 Physical input-output table for bus 1 (Scenario I = Overnight charging)*

| Processes | | | P1 | P2 | P3 | P4 | Final demand | Total output |
|---|---|---|---|---|---|---|---|---|
| P1 | Battery production | fully charged battery | - | 0.10 | 0 | 0 | 0 | 0.10 |
| P2 | Bus operation | partially discharged battery | 0 | - | 0.10 | 0 | 0 | 0.10 |
| P3 | Overnight charging | fully charged battery | 0 | 0 | - | 0.10 | 0 | 0.10 |
| P4 | Bus operation | end-of-life battery | 0 | 0 | 0 | - | 0.10 | 0.10 |
| **Primary inputs** | | | | | | | **Total primary input use** | |
| r1 | Aluminium | kg | 4.60 | 0 | 0 | 0 | 4.60 | |
| r2 | Lithium | kg | 0.25 | 0 | 0 | 0 | 0.25 | |
| r3 | Graphite | kg | 3.75 | 0 | 0 | 0 | 3.75 | |
| r4 | Workforce | person hour | N/A | 17 | 0 | 5651 | 5668 | |
| r5 | Electricity | kWh | 879 | 0 | 121160 | 0 | 122039 | |
| **By-products** | | | | | | | **Total by-products** | |
| w1 | CO2 | kg | 570 | 0 | 78633 | 0 | 79203 | |

*Figure 24 Physical input-output table for bus 2 (Scenario I = Overnight charging)*

| Processes | | | P1 | P2 | P3 | P4 | Final demand | Total output |
|---|---|---|---|---|---|---|---|---|
| P1 | Battery production | fully charged battery | - | 0.08 | 0 | 0 | 0 | 0.08 |
| P2 | Bus operation | partially discharged battery | 0 | - | 0.08 | 0 | 0 | 0.08 |
| P3 | Overnight charging | fully charged battery | 0 | 0 | - | 0.08 | 0 | 0.08 |
| P4 | Bus operation | end-of-life battery | 0 | 0 | 0 | - | 0.08 | 0.08 |
| **Primary inputs** | | | | | | | **Total primary input use** | |
| r1 | Aluminium | kg | 3.92 | 0 | 0 | 0 | 3.92 | |
| r2 | Lithium | kg | 0.21 | 0 | 0 | 0 | 0.21 | |
| r3 | Graphite | kg | 3.20 | 0 | 0 | 0 | 3.20 | |
| r4 | Workforce | person hour | N/A | 17 | 0 | 5001 | 5018 | |
| r5 | Electricity | kWh | 749 | 0 | 106080 | 0 | 106829 | |
| **By-products** | | | | | | | **Total by-products** | |
| w1 | CO2 | kg | 486 | 0 | 68846 | 0 | 69332 | |

*Figure 25 Physical input-output table for bus 3 (Scenario I = Overnight charging)*

| Processes | | | P1 | P2 | P3 | P4 | Final demand | Total output |
|---|---|---|---|---|---|---|---|---|
| P1 | Battery production | fully charged battery | - | 0.08 | 0 | 0 | 0 | 0.08 |
| P2 | Bus operation and recharging | partially discharged battery | 0 | - | 0.08 | 0 | 0 | 0.08 |
| P3 | Overnight charging | fully charged battery | 0 | 0 | - | 0.08 | 0 | 0.08 |
| P4 | Bus operation and recharging | end-of-life battery | 0 | 0 | 0 | - | 0.08 | 0.08 |
| **Primary inputs** | | | | | | | **Total primary input use** | |
| r1 | Aluminium | kg | 1.45 | 0 | 0 | 0 | 1.45 | |
| r2 | Lithium | kg | 0.08 | 0 | 0 | 0 | 0.08 | |
| r3 | Graphite | kg | 1.18 | 0 | 0 | 0 | 1.18 | |
| r4 | Workforce | person hour | N/A | 18 | 0 | 6222 | 6240 | |
| r5 | Electricity | kWh | 277 | 262 | 31074 | 90639 | 122253 | |
| **By-products** | | | | | | | **Total by-products** | |
| w1 | CO2 | kg | 180 | 170 | 20167 | 58825 | 79342 | |

*Figure 26 Physical input-output table for bus 1 (Scenario II = Overnight and opportunity charging)*

| Processes | | | P1 | P2 | P3 | P4 | Final demand | Total output |
|---|---|---|---|---|---|---|---|---|
| P1 | Battery production | fully charged battery | - | 0.07 | 0 | 0 | 0 | 0.07 |
| P2 | Bus operation and recharging | partially discharged battery | 0 | - | 0.07 | 0 | 0 | 0.07 |
| P3 | Overnight charging | fully charged battery | 0 | 0 | - | 0.07 | 0 | 0.07 |
| P4 | Bus operation and recharging | end-of-life battery | 0 | 0 | 0 | - | 0.07 | 0.07 |
| **Primary inputs** | | | | | | | **Total primary input use** | |
| r1 | Aluminium | kg | 1.40 | 0 | 0 | 0 | 1.40 | |
| r2 | Lithium | kg | 0.08 | 0 | 0 | 0 | 0.08 | |
| r3 | Graphite | kg | 1.14 | 0 | 0 | 0 | 1.14 | |
| r4 | Workforce | person hour | N/A | 18 | 0 | 5910 | 5928 | |
| r5 | Electricity | kWh | 267 | 262 | 31074 | 86044 | 117647 | |
| **By-products** | | | | | | | **Total by-products** | |
| w1 | CO2 | kg | 173 | 170 | 20167 | 55842 | 76353 | |

*Figure 27 Physical input-output table for bus 2 (Scenario II = Overnight and opportunity charging)*

| Processes | | | P1 | P2 | P3 | P4 | Final demand | Total output |
|---|---|---|---|---|---|---|---|---|
| P1 | Battery production | fully charged battery | - | 0.05 | 0 | 0 | 0 | 0.05 |
| P2 | Bus operation and recharging | partially discharged battery | 0 | - | 0.05 | 0 | 0 | 0.05 |
| P3 | Overnight charging | fully charged battery | 0 | 0 | - | 0.05 | 0 | 0.05 |
| P4 | Bus operation and recharging | end-of-life battery | 0 | 0 | 0 | - | 0.05 | 0.05 |
| **Primary inputs** | | | | | | | **Total primary input use** | |
| r1 | Aluminium | kg | 0.91 | 0 | 0 | 0 | 0.91 | |
| r2 | Lithium | kg | 0.05 | 0 | 0 | 0 | 0.05 | |
| r3 | Graphite | kg | 0.74 | 0 | 0 | 0 | 0.74 | |
| r4 | Workforce | person hour | N/A | 13 | 0 | 3654 | 3666 | |
| r5 | Electricity | kWh | 174 | 174 | 31074 | 49512 | 80934 | |
| **By-products** | | | | | | | **Total by-products** | |
| w1 | CO2 | kg | 113 | 113 | 20167 | 32133 | 52526 | |

*Figure 28 Physical input-output table for bus 3 (Scenario II = Overnight and opportunity charging)*

| Processes | | | P1 | P2 | P3 | P4 | Final demand |
|---|---|---|---|---|---|---|---|
| P1 | Battery production | fully charged battery | - | 0.09 | 0 | 0 | 0 |
| P2 | Bus operation and recharging | partially discharged battery | 0 | - | 0.09 | 0 | 0 |
| P3 | Charging | partially discharged battery | 0 | 0 | - | 0.09 | 0 |
| P4 | Bus operation and recharging | end-of-life battery | 0 | 0 | 0 | - | 0.09 |
| **Primary inputs** | | | | | | | **Total primary input use** |
| r1 | Aluminium | kg | 0.67 | 0 | 0 | 0 | 0.67 |
| r2 | Lithium | kg | 0.04 | 0 | 0 | 0 | 0.04 |
| r3 | Graphite | kg | 0.55 | 0 | 0 | 0 | 0.55 |
| r4 | Workforce | person hour | N/A | 18 | 0 | 6274 | 6292 |
| r5 | Electricity | kWh | 128 | 255 | 8403 | 88811 | 97596 |
| **By-products** | | | | | | | **Total by-products** |
| w1 | CO2 | kg | 83 | 165 | 5454 | 57638 | 63340 |

*Figure 29 Physical input-output table for bus 1 (Scenario III = Opportunity charging)*

| Processes | | | P1 | P2 | P3 | P4 | Final demand | Total output |
|---|---|---|---|---|---|---|---|---|
| P1 | Battery production | fully charged battery | - | 0.09 | 0 | 0 | 0 | 0.09 |
| P2 | Bus operation and recharging | partially discharged battery | 0 | - | 0.09 | 0 | 0 | 0.09 |
| P3 | Charging | partially discharged battery | 0 | 0 | - | 0.09 | 0 | 0.09 |
| P4 | Bus operation and recharging | end-of-life battery | 0 | 0 | 0 | - | 0.09 | 0.09 |
| **Primary inputs** | | | | | | | **Total primary input use** | |
| r1 | Aluminium | kg | 0.65 | 0 | 0 | 0 | 0.65 | |
| r2 | Lithium | kg | 0.03 | 0 | 0 | 0 | 0.03 | |
| r3 | Graphite | kg | 0.53 | 0 | 0 | 0 | 0.53 | |
| r4 | Workforce | person hour | N/A | 18 | 0 | 5962 | 5980 | |
| r5 | Electricity | kWh | 123 | 185 | 8403 | 85269 | 93981 | |
| **By-products** | | | | | | | **Total by-products** | |
| w1 | CO2 | kg | 80 | 120 | 5454 | 55340 | 60994 | |

*Figure 30 Physical input-output table for bus 2 (Scenario III = Opportunity charging)*

| Processes | | | P1 | P2 | P3 | P4 | Final demand | Total output |
|---|---|---|---|---|---|---|---|---|
| P1 | Battery production | fully charged battery | - | 0.06 | 0 | 0 | 0 | 0.06 |
| P2 | Bus operation and recharging | partially discharged battery | 0 | - | 0.06 | 0 | 0 | 0.06 |
| P3 | Charging | partially discharged battery | 0 | 0 | - | 0.06 | 0 | 0.06 |
| P4 | Bus operation and recharging | end-of-life battery | 0 | 0 | 0 | - | 0.06 | 0.06 |
| **Primary inputs** | | | | | | | **Total primary input use** | |
| r1 | Aluminium | kg | 0.42 | 0 | 0 | 0 | 0.42 | |
| r2 | Lithium | kg | 0.02 | 0 | 0 | 0 | 0.02 | |
| r3 | Graphite | kg | 0.34 | 0 | 0 | 0 | 0.34 | |
| r4 | Workforce | person hour | N/A | 13 | 0 | 3654 | 3666 | |
| r5 | Electricity | kWh | 81 | 116 | 7200 | 54046 | 61442 | |
| **By-products** | | | | | | | **Total by-products** | |
| w1 | CO2 | kg | 157 | 75 | 4673 | 35076 | 39980 | |

*Figure 31 Physical input-output table for bus 3 (Scenario III = Opportunity charging)*

The physical input-output tables above present the physical flows per battery and therefore per bus. The outcome of each scenario can be determined by adding up the calculations for all three buses that belong to the scenario. The aggregation of the buses per scenario is given in table 10.

| | | **SCENARIO I** | **SCENARIO II** | **SCENARIO III** |
|---|---|---|---|---|
| **TOTAL PRODUCTION** | | | | |
| BATTERIES | unit | 0.27 | 0.20 | 0.23 |
| | | | | |
| **TOTAL PRIMARY INPUT USE** | | | | |
| ALUMINIUM | kg | 13.11 | 3.76 | 1.74 |
| LITHIUM | kg | 0.70 | 0.20 | 0.09 |
| GRAPHITE | kg | 10.70 | 3.07 | 1.42 |
| WORKFORCE | person hour | 16,614 | 15,834 | 15,938 |
| ELECTRICITY | kWh | 350,906 | 320,834 | 253,019 |
| | | | | |
| **TOTAL BY-PRODUCTS** | | | | |
| $CO_2$ | kg | 227,738 | 208,221 | 164,314 |

*Table 10 Summary of the physical flows per scenario*

Table 10 shows that scenario III produces 164 ton $CO_2$ per year. With a yearly emission of 228 ton, most of the $CO_2$ is released with scenario I. $CO_2$ emission can mostly be attributed to the charging process in the supply chain of the bus transportation. Most of the electric energy is consumed in scenario I, while the difference with scenario II is relatively small. The large energy consumption of the buses is the result of using larger battery sizes, which negatively impact the weight of the bus. It can be observed that the impact of the battery production on the $CO_2$ emission increases as the battery size increases. That is to say, the impact of the battery production phase on the $CO_2$ emission is the largest for scenario

I, as the largest batteries are used here. Production of larger batteries require more energy and material content. However the impact of battery production is negligible in all scenarios, considering the $CO_2$ emission resulting from the electricity use. The battery production process is, still, responsible for the use of important materials, such as graphite. Natural graphite is a critical raw material that has a high supply risk and its use can contribute to resource depletion. As the largest batteries are used in scenario I, the amount of graphite needed for the production is also the largest for this scenario.

There are not huge differences in workforce between the scenarios. The required workforce, still, seems to be least for scenario II and III. Scenario II and III have more flexibility with respect to the planning of the buses, which is why less workforce, in terms of bus drivers, is needed. This flexibility arises from the fact that the buses can make more rides per day, as an advantage of charging during the day. The batteries with overnight charging don't have this possibility and therefore can only make a limited number of rides per day.

All in all, it is shown that scenario III is the most environmentally sustainable scenario. Considering all scenarios, scenario III causes the least $CO_2$ emission as a result of less material and electricity consumption.

## 6.2. Economic sustainability

This section presents the monetary input-output tables for the scenarios. The physical input-output tables from the previous section are integrated into the monetary EIO tables to calculate the economic performance of the supply chain of bus transportation. The monetary input-output tables display per battery the costs and benefits associated with physical flows of the supply chain of bus transportation. Each table presents the monetary flows of one battery. At the end of the section the monetary tables of each scenario are summed in table 11.

| **Processes (€)** | | | P1 | P2 | P3 | P4 | **Final demand** | **Total output** |
|---|---|---|---|---|---|---|---|---|
| P1 | Battery production | fully charged battery | - | 7587 | 0 | 0 | 0 | 7587 |
| P2 | Bus operation | partially discharged battery | 0 | - | 7587 | 0 | 0 | 7587 |
| P3 | Overnight charging | fully charged battery | 0 | 0 | - | 7587 | 0 | 7587 |
| P4 | Bus operation | end-of-life battery | 0 | 0 | 0 | - | 7587 | 7587 |
| **Primary inputs** | | | | | | | **Total primary input use** | |
| r1 | Aluminium | kg | 7.59 | 0 | 0 | 0 | 7.59 | |
| r2 | Lithium | kg | 0.17 | 0 | 0 | 0 | 0.17 | |
| r3 | Graphite | kg | 3.68 | 0 | 0 | 0 | 3.68 | |
| r4 | Workforce | person hour | N/A | 224 | 0 | 77966 | 78190 | |
| r5 | Electricity | kWh | 202 | 0 | 27867 | 0 | 28069 | |
| **By-products** | | | | | | | **Total by-products** | |
| w1 | CO2 | kg | 43 | 0 | 5897 | 0 | 5940 | |

*Figure 32 Monetary input-output table for bus 1 (Scenario I = Overnight charging)*

| **Processes (€)** | | | P1 | P2 | P3 | P4 | **Final demand** | **Total output** |
|---|---|---|---|---|---|---|---|---|
| P1 | Battery production | fully charged battery | - | 7587 | 0 | 0 | 0 | 7587 |
| P2 | Bus operation | partially discharged battery | 0 | - | 7587 | 0 | 0 | 7587 |
| P3 | Overnight charging | fully charged battery | 0 | 0 | - | 7587 | 0 | 7587 |
| P4 | Bus operation | end-of-life battery | 0 | 0 | 0 | - | 7587 | 7587 |
| **Primary inputs** | | | | | | | **Total primary input use** | |
| r1 | Aluminium | kg | 7.59 | 0 | 0 | 0 | 7.59 | |
| r2 | Lithium | kg | 0.17 | 0 | 0 | 0 | 0.17 | |
| r3 | Graphite | kg | 3.68 | 0 | 0 | 0 | 3.68 | |
| r4 | Workforce | person hour | N/A | 224 | 0 | 74537 | 74761 | |
| r5 | Electricity | kWh | 202 | 0 | 27867 | 0 | 28069 | |
| **By-products** | | | | | | | **Total by-products** | |
| w1 | CO2 | kg | 43 | 0 | 5897 | 0 | 5940 | |

*Figure 33 Monetary input-output table for bus 2 (Scenario I = Overnight charging)*

| Processes (€) | | | P1 | P2 | P3 | P4 | Final demand | Total output |
|---|---|---|---|---|---|---|---|---|
| P1 | Battery production | fully charged battery | - | 6468 | 0 | 0 | 0 | 6468 |
| P2 | Bus operation | partially discharged battery | 0 | - | 6468 | 0 | 0 | 6468 |
| P3 | Overnight charging | fully charged battery | 0 | 0 | - | 6468 | 0 | 6468 |
| P4 | Bus operation | end-of-life battery | 0 | 0 | 0 | - | 6468 | 6468 |
| **Primary inputs** | | | | | | | **Total primary input use** | |
| r1 | Aluminium | kg | 6.47 | 0 | 0 | 0 | 6.47 | |
| r2 | Lithium | kg | 0.14 | 0 | 0 | 0 | 0.14 | |
| r3 | Graphite | kg | 3.13 | 0 | 0 | 0 | 3.13 | |
| r4 | Workforce | person hour | N/A | 224 | 0 | 65963 | 66187 | |
| r5 | Electricity | kWh | 172 | 0 | 24398 | 0 | 24571 | |
| **By-products** | | | | | | | **Total by-products** | |
| w1 | CO2 | kg | 36 | 0 | 5163 | 0 | 5200 | |

*Figure 34 Monetary input-output table for bus 3 (Scenario I = Overnight charging)*

| Processes (€) | | | P1 | P2 | P3 | P4 | Final demand | Total output |
|---|---|---|---|---|---|---|---|---|
| P1 | Battery production | fully charged battery | - | 2391 | 0 | 0 | 0 | 2391 |
| P2 | Bus operation and recharging | partially discharged battery | 0 | - | 2391 | 0 | 0 | 2391 |
| P3 | Overnight charging | fully charged battery | 0 | 0 | - | 2391 | 0 | 2391 |
| P4 | Bus operation and recharging | end-of-life battery | 0 | 0 | 0 | - | 2391 | 2391 |
| **Primary inputs** | | | | | | | **Total primary input use** | |
| r1 | Aluminium | kg | 2.39 | 0 | 0 | 0 | 2.39 | |
| r2 | Lithium | kg | 0.05 | 0 | 0 | 0 | 0.05 | |
| r3 | Graphite | kg | 1.16 | 0 | 0 | 0 | 1.16 | |
| r4 | Workforce | person hour | N/A | 237 | 0 | 82068 | 82306 | |
| r5 | Electricity | kWh | 64 | 60 | 7147 | 20847 | 28118 | |
| **By-products** | | | | | | | **Total by-products** | |
| w1 | CO2 | kg | 13 | 13 | 1513 | 4412 | 5951 | |

*Figure 35 Monetary input-output table for bus 1 (Scenario II = Overnight and opportunity charging)*

| Processes (€) | | | P1 | P2 | P3 | P4 | Final demand | Total output |
|---|---|---|---|---|---|---|---|---|
| P1 | Battery production | fully charged battery | - | 2304 | 0 | 0 | 0 | 2304 |
| P2 | Bus operation and recharging | partially discharged battery | 0 | - | 2304 | 0 | 0 | 2304 |
| P3 | Overnight charging | fully charged battery | 0 | 0 | - | 2304 | 0 | 2304 |
| P4 | Bus operation and recharging | end-of-life battery | 0 | 0 | 0 | - | 2304 | 2304 |
| **Primary inputs** | | | | | | | **Total primary input use** | |
| r1 | Aluminium | kg | 2.30 | 0 | 0 | 0 | 2.30 | |
| r2 | Lithium | kg | 0.05 | 0 | 0 | 0 | 0.05 | |
| r3 | Graphite | kg | 1.12 | 0 | 0 | 0 | 1.12 | |
| r4 | Workforce | person hour | N/A | 237 | 0 | 77953 | 78190 | |
| r5 | Electricity | kWh | 61 | 60 | 7147 | 19790 | 27059 | |
| **By-products** | | | | | | | **Total by-products** | |
| w1 | CO2 | kg | 13 | 13 | 1513 | 4188 | 5726 | |

*Figure 36 Monetary input-output table for bus 2 (Scenario II = Overnight and opportunity charging)*

| Processes (€) | | | P1 | P2 | P3 | P4 | Final demand | Total output |
|---|---|---|---|---|---|---|---|---|
| P1 | Battery production | fully charged battery | - | 1503 | 0 | 0 | 0 | 1503 |
| P2 | Bus operation and recharging | partially discharged battery | 0 | - | 1503 | 0 | 0 | 1503 |
| P3 | Overnight charging | fully charged battery | 0 | 0 | - | 1503 | 0 | 1503 |
| P4 | Bus operation and recharging | end-of-life battery | 0 | 0 | 0 | - | 1503 | 1503 |
| **Primary inputs** | | | | | | | **Total primary input use** | |
| r1 | Aluminium | kg | 1.50 | 0 | 0 | 0 | 1.50 | |
| r2 | Lithium | kg | 0.03 | 0 | 0 | 0 | 0.03 | |
| r3 | Graphite | kg | 0.73 | 0 | 0 | 0 | 0.73 | |
| r4 | Workforce | person hour | N/A | 165 | 0 | 48190 | 48355 | |
| r5 | Electricity | kWh | 40 | 40 | 7147 | 11388 | 18615 | |
| **By-products** | | | | | | | **Total by-products** | |
| w1 | CO2 | kg | 8 | 8 | 1513 | 2410 | 3939 | |

*Figure 37 Monetary input-output table for bus 3 (Scenario II = Overnight and opportunity charging)*

| Processes (€) | | | P1 | P2 | P3 | P4 | Final demand | Total output |
|---|---|---|---|---|---|---|---|---|
| P1 | Battery production | fully charged battery | - | 1103 | 0 | 0 | 0 | 1103 |
| P2 | Bus operation and recharging | partially discharged battery | 0 | - | 1103 | 0 | 0 | 1103 |
| P3 | Charging | partially discharged battery | 0 | 0 | - | 1103 | 0 | 1103 |
| P4 | Bus operation and recharging | end-of-life battery | 0 | 0 | 0 | - | 1103 | 1103 |
| **Primary inputs** | | | | | | | **Total primary input use** | |
| r1 | Aluminium | kg | 1.10 | 0 | 0 | 0 | 1.10 | |
| r2 | Lithium | kg | 0.03 | 0 | 0 | 0 | 0.03 | |
| r3 | Graphite | kg | 0.54 | 0 | 0 | 0 | 0.54 | |
| r4 | Workforce | person hour | N/A | 237 | 0 | 82754 | 82991 | |
| r5 | Electricity | kWh | 29 | 59 | 1933 | 20426 | 22447 | |
| **By-products** | | | | | | | **Total by-products** | |
| w1 | CO2 | kg | 6 | 12 | 409 | 4323 | 4751 | |

*Figure 38 Monetary input-output table for bus 1 (Scenario III = Opportunity charging)*

| Processes (€) | | | P1 | P2 | P3 | P4 | Final demand | Total output |
|---|---|---|---|---|---|---|---|---|
| P1 | Battery production | fully charged battery | - | 1066 | 0 | 0 | 0 | 1066 |
| P2 | Bus operation and recharging | partially discharged battery | 0 | - | 1066 | 0 | 0 | 1066 |
| P3 | Charging | partially discharged battery | 0 | 0 | - | 1066 | 0 | 1066 |
| P4 | Bus operation and recharging | end-of-life battery | 0 | 0 | 0 | - | 1066 | 1066 |
| **Primary inputs** | | | | | | | **Total primary input use** | |
| r1 | Aluminium | kg | 1.06 | 0 | 0 | 0 | 1.06 | |
| r2 | Lithium | kg | 0.02 | 0 | 0 | 0 | 0.02 | |
| r3 | Graphite | kg | 0.52 | 0 | 0 | 0 | 0.52 | |
| r4 | Workforce | person hour | N/A | 237 | 0 | 78639 | 78876 | |
| r5 | Electricity | kWh | 28 | 43 | 1933 | 19645 | 21648 | |
| **By-products** | | | | | | | **Total by-products** | |
| w1 | CO2 | kg | 6 | 9 | 409 | 4150 | 4575 | |

*Figure 39 Monetary input-output table for bus 2 (Scenario III = Opportunity charging)*

| Processes (€) | | | P1 | P2 | P3 | P4 | Final demand | Total output |
|---|---|---|---|---|---|---|---|---|
| P1 | Battery production | fully charged battery | - | 696 | 0 | 0 | 0 | 696 |
| P2 | Bus operation and recharging | partially discharged battery | 0 | - | 696 | 0 | 0 | 696 |
| P3 | Charging | partially discharged battery | 0 | 0 | - | 696 | 0 | 696 |
| P4 | Bus operation and recharging | end-of-life battery | 0 | 0 | 0 | - | 696 | 696 |
| **Primary inputs** | | | | | | | **Total primary input use** | |
| r1 | Aluminium | kg | 0.70 | 0 | 0 | 0 | 0.70 | |
| r2 | Lithium | kg | 0.02 | 0 | 0 | 0 | 0.02 | |
| r3 | Graphite | kg | 0.34 | 0 | 0 | 0 | 0.34 | |
| r4 | Workforce | person hour | N/A | 165 | 0 | 48190 | 48355 | |
| r5 | Electricity | kWh | 19 | 27 | 1656 | 12430 | 14132 | |
| **By-products** | | | | | | | **Total by-products** | |
| w1 | CO2 | kg | 12 | 6 | 350 | 2631 | 2999 | |

*Figure 40 Monetary input-output table for bus 3 (Scenario III = Opportunity charging)*

| **TOTAL PRODUCTION** | **SCENARIO I** | **SCENARIO II** | **SCENARIO III** |
|---|---|---|---|
| BATTERY | € 21,641 | € 5,397 | € 2,865 |
| | | | |
| **TOTAL PRIMARY INPUT USE** | | | |
| ALUMINIUM | € 21.64 | € 6.20 | € 2,86 |
| LITHIUM | € 0.48 | € 0.14 | € 0,06 |
| GRAPHITE | € 10.49 | € 3.00 | € 1.39 |
| WORKFORCE | € 219,139 | € 208,850 | € 210,222 |
| ELECTRICITY | € 80,708 | € 73,792 | € 58,227 |
| | | | |
| **TOTAL WASTES** | | | |
| $CO_2$ | € 17,080 | € 15,617 | € 12,324 |
| | | | |
| **TOTAL INVESTMENT COSTS** | € 14,950 | € 46,582 | € 34,965 |
| | | | |
| **TOTAL COSTS** | € 353,551 | € 350.247 | € 318,608 |

*Table 11 Summary of the monetary flows per scenario*

Table 11 presents the monetary flows of the supply chain of bus transportation on a year basis. First, it is remarkable that scenario I has relatively high battery costs. From this, it can be concluded that as the battery becomes larger, the total input use (in particular material requirement) also increases, which result in higher costs. Secondly, aluminium is the material that is used in largest quantities in all scenarios and thereby is the most expensive material component of the battery. Workforce appears to be the most expensive input in the supply chain, with the differences between the scenarios being relatively small. Nevertheless, scenario III requires the least amount of workforce, which is a consequence of the flexibility with planning of the rides. Scenario III has the lowest electricity consumption, which is directly related to the battery size. A smaller battery, after all, causes less consumption. Figure 41 shows the average contribution of a particular component of the monetary input-output model to the total costs of the supply chain. The figure shows that the highest costs per year are made for the workforce, i.e. employment of bus drivers. Then, electricity costs and investment costs are the highest contributors with 21% and 10% respectively.

It can be observed that scenario I results in the highest environmental costs and lowest investment costs. Scenario III, on the other hand, has the lowest environmental costs and relatively high investment costs, compared to that of scenario I. However, when we look at the total costs of the supply chain, it can be observed that scenario III results in the lowest costs per year. The implementation of scenario I requires € 353,551 per year, while the total costs for scenario III is equal to € 318,608 per year.

Scenario III results in the least primary input use and thereby release of $CO_2$, causing the least environmental costs. The battery costs are very low, due to the limited battery capacity in the buses. The infrastructure costs are high compared to scenario I. This is mainly due to the purchase of a more expensive charging unit and the installation of high voltage electric connection.

The costs in scenario II are € 350,247 per year. Apart from the battery, material and investment costs, the monetary values for scenarios I and II are pretty close together. The investment costs are the highest for this scenario due to the installation of infrastructure at two locations. Scenario II results in the second expensive charging strategy after scenario I.

All in all, the physical tables show that Scenario III: Opportunity charging is both the most environmentally and economically sustainable charging strategy.

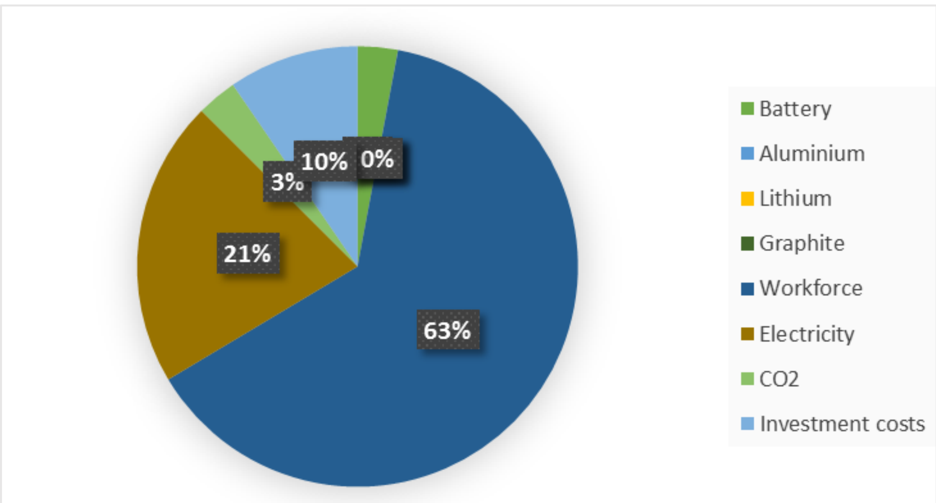



*Figure 41 The average contribution of a component of the monetary EIO to the total costs of the supply chain*

# 7. Conclusion & future research

## 7.1. Conclusion

While different zero-emission buses are already introduced in the Netherlands, it is not studied well enough what its impact will be on the economy and the environment. Currently, a lot of research is being done on a concession level, where the focus is to find a suitable charging strategy at minimum cost. It is the operation phase that is mostly focused on, while the processes prior and after are not given enough attention. The zero-emission public bus transport is undoubtedly a sustainable solution and clearly much better than the conventional bus transport, however, it is not known how sustainable it is, and if there is room for improvement. In other words, only looking at the use of the emission-free buses does not say enough about the environmental and economic sustainability of the zero-emission public bus transport. This study fills this gap to understand the significance of batteries in the supply chain of electric bus transportation.

The sustainability of the supply chain of bus transportation is strongly influenced by the battery size, whose impact is quantified via scenario analysis. The battery size and the charging strategy are heavily related to each other. While a bigger battery allows overnight charging, smaller batteries are only efficient with opportunity charging. The battery has a considerable impact on the energy consumption in the operation phase, but also on the production phase and the end of life treatment of the batteries. Not only the battery size but also the battery chemistry is of significant importance, as it influences the energy density and battery life. The battery choice is thus a factor that influences the whole supply chain of electric bus transportation and thereby has a serious impact on its sustainability.

There is uncertainty concerning the batteries, which affects the relationship between the actors in the supply chain. The battery type is revealed when a bus supplier is being chosen, i.e. the bus manufacturer chooses the battery to be installed in the bus. The choice for a bus supplier and other suppliers in the supply chain of bus transportation is dependent on the local need. Furthermore, the fast-evolving battery market contributes to this uncertainty. It impacts the choice of which batteries will be used in the buses and how they will be treated at their end of life. Due to the shift towards reduced valuable material in battery chemistries, the industry is concerned that there could be reduced incentives for effective recycling.

In this study, an EIO model is adopted to analyze the environmental and economic sustainability of the battery bus transportation in the specific case of station Z. The case study gives insight into the energy consumption, $CO_2$ emissions and required investment of the adoption of three charging strategies. The research does not only allow us to compare charging strategies, but also different batteries in terms of size. The outcome of the enterprise input-output modeling shows that the majority of $CO_2$ emission of the bus transportation supply chain originates from fuel-related emissions, and not from battery-related emissions. This confirms that the origin of the electricity used for the charging of the buses is key for the reduction of emissions from the buses. Ensuring the usage of renewable energy will drastically reduce the impact of bus transportation.

With respect to charging strategies, it can be concluded that the most environmentally and economically sustainable scenario is scenario III: Opportunity charging. This charging strategy is characterized by small battery capacity and a small SOC window. This scenario makes use of very small batteries, compared to the other scenarios. The benefits of using batteries with small capacity can be observed in the results, i.e. less material and electricity use in both production and operation processes, resulting in less $CO_2$ emission. Furthermore, a smaller battery requires using small SOC windows, which prolongs battery life. Among all scenarios, the batteries in scenario III have the longest expected lifetime. In addition, the results of the analysis show that larger batteries could not only lead to higher battery-related emissions, but also to higher fuel-associated emissions, as the energy consumption increases. Compared to a small battery, using a relatively small SOC window with a large battery reflects in a higher weight of the bus and therefore causes higher energy consumption. Hence, small SOC windows are only efficient with smaller batteries. It can, therefore, be concluded that a reduction of the weight of the battery and the related electricity consumption will drastically reduce the impacts linked to electricity generation.

This study shows that the supply chain of scenario III is the most environmentally and economically supply chain among all with total costs of € 318,608 per year. Moreover, opportunity charging in combination with 79 kWh batteries is identified as the most suitable charging strategy. Opportunity charging requires the installment of expensive charging units in many locations, the exact number depending on the traveled distance and the number of buses that need to be recharged at the same time. In our scenario analysis, we assume that the charging infrastructure is only being used by three buses of bus line Y, however, in reality, the infrastructure is being shared with many bus lines so that the charging infrastructure costs can be divided. Practically, one fast charger is required per 5 buses (Vervoerregio Amsterdam, 2018). Hence, when evaluated on a concession level, the investment costs per bus line can be much lower.

The business model can be extended to a case where an open-loop supply chain is created. In such a model, aluminium in the batteries can be recycled for use in the production of other bus components by the bus manufacturer. This would be a complete circular model in line with the EU's regional development strategies, particularly when we consider that sustainable development should be on a local level. Specifically, in the EV batteries sphere, the recycling potential is significant as these batteries may be easier to collect if a dedicated system of return is established. Aluminium can also be sold to (local) parties outside the supply chain. The material produced from battery recycling can be used by the automotive industry, depending on the quality of the recycled material. Hence, there is a serious incentive to create a local production model, which can be investigated in the future.

## 7.2. Future research

Our business model considers a simple case in which only three actors are involved in the supply chain. However, we should consider that there are actually more parties involved, e.g. bus manufacturer, energy provider and in particular the end of life treatment process should be considered in a future analysis. There are two interesting scenarios to consider for future analysis: 1) recycling of battery key raw materials (aluminium) and 2) reuse the battery cells in a stationary storage system to charge the buses. Currently, in the EU the value of the retrieved raw material is often not sufficient to pay for the labor needed to extract the material, hence there might be no business case at the moment for recycling these batteries. This will change, however, as the EV industry grows.

This research can also be extended by including material and waste flows other than used in this study. In this research, we assume LFP batteries, which contain the three key raw materials included in this study. However, there are other common battery chemistries that contain other (critical) raw materials, like nickel and cobalt. These materials provide a significant incentive for recycling due to their economic importance. In particular, the content of nickel is increasing in many battery chemistries. The industry has been improving NMC technology by steadily increasing the nickel content in each cathode generation. Hence, the current study can also be expanded by evaluating scenarios that include other battery chemistries. NMC batteries are currently among the most used batteries for EVs and this is expected to increase in the near future.

Furthermore, the EIO modeling shows that in all charging scenarios the highest costs per year are made for the workforce. This stresses the importance of vehicle scheduling in minimizing costs. This research focuses mainly on the dimensioning of the battery capacity and charging infrastructure for a single bus line, without considering the vehicle scheduling in detail. With opportunity charging, the bus schedule must provide sufficient charging times at the station. This results in a strong linkage between the vehicle scheduling and infrastructure planning. This study can be expanded to the entire bus network taking especially the influence of vehicle scheduling on the system design into account.

# References

Ahmadi, L., Yip, A., Fowler, M., Young, S. B., & Fraser, R. A. (2014). Environmental feasibility of re-use of electric vehicle batteries. *Sustainable Energy Technologies and Assessments*, 64-74.

Albino, V., & Kühtz, S. (2004). Enterprise input–output model for local sustainable development—the case of a tiles manufacturer in Italy. *Resources, Conservation and Recycling, 41(3)*, 165-176.

Albino, V., Dietzenbacher, E., & Kühtz, S. (2003). Analysing materials and energy flows in an industrial district using an enterprise input–output model. *Economic Systems Research, 15(4)*, 457-480.

Albino, V., Izzo, C., & Kühtz, S. (2002). Input–output models for the analysis of a local/global supply chain. *International journal of production economics, 78(2)*, 119-131.

Alexandru, S., Jeswiet, J., & Kie Soo, V. (2015). Opportunities to Improve Recycling of Automotive Lithium Ion Batteries. *Life Cycle Engineering*, 752-757.

APPM. (2019, januari 28). *Adviesrapport Marktdialoog zero emissie busvervoer.* Retrieved from platformduurzaamovenspoor.

Battery University. (2019). *BU-808: How to Prolong Lithium-based Batteries*. Retrieved from Batteryuniversity: https://batteryuniversity.com/learn/article/how_to_prolong_lithium_based_batteries

Batteryspace.com. (2019, April). *Lithium Iron Phosphate (LiFePO4) Battery.* Retrieved from Batteryspace: https://www.batteryspace.com/prod-specs/9055.pdf

Berckmans, G., Messagie, M., Smekens, J., Omar, N., Vanhaverbeke, L., & Van Mierlo, J. (2017). Cost Projection of State of the Art Lithium-Ion Batteries for Electric Vehicles Up to 2030. *Energy Efficiency Analysis of Building Materials*.

Bocken, N., de Pauw, I., Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering*, 308-320.

Campanari, S., Manzolini, G., & De la Iglesia, F. G. (2009). Energy analysis of electric vehicles using batteries or fuel cells through well-to-wheel driving cycle simulations. *Journal of Power Sources, 186(2)*, 464-477.

Chertow, M. (2007). "Uncovering" industrial symbiosis. *Journal of Industrial Ecology*, 11-30.

Chester, M. V., & Horvath, A. (2009). nvironmental assessment of passenger transportation should include infrastructure and supply chains. *Environmental research letters, 4(2)*, 024008.

Co2emissiefactoren. (2019, March 28). *Lijst emissiefactoren*. Retrieved from co2emissiefactoren: https://www.co2emissiefactoren.nl/lijst-emissiefactoren/#elektriciteit

CROW. (2018). *Poster Milieuprestatie ov-bussen, editie 2018.* Retrieved from CROW: https://www.crow.nl/publicaties/poster-milieuprestatie-ov-bussen-2018-pdf

CROW. (2019, Januari 28). *Verdubbeling aantal zero-emissiebussen in 2018 en 2019*. Retrieved from CROW: https://www.crow.nl/kennis/bibliotheek-verkeer-en-vervoer/kennisdocumenten/verdubbeling-aantal-zero-emissiebussen-in-2018-en

Curry, C. (2017). Lithium-ion battery costs and market. *Bloomberg New Energy Finance, 5*.

Drabik, E., & Rizos, V. (2018). *Prospects for electric vehicle batteries in a circular economy.* Brussels: CEPS.

Dragt, M. (2018). *Milieuprestatie van ov-bussen 2018.* Retrieved from CROW: https://www.crow.nl/downloads/pdf/verkeer-en-vervoer/crow-kpvv/poster-milieukwaliteit/crow-kpvv-poster-millieukwaliteit-2018.aspx?ext=.

EEA. (2016). *Electric vehicles in Europe.* Copenhagen: Publications office of the European Union.

EEA. (2017). *Circular by design — products in the circular economy.* Retrieved from European Environment Agency: https://www.eea.europa.eu/publications/circular-by-design

EEA. (2018). *Electric vehicles from life cycle and circular economy perspectives.* Luxembourg: Publications Office of the European Union.

Egede, P., Dettmer, T., Hermann, C., & Kara, S. (2015). Life Cycle Assessment of Electric Vehicles – A Framework to Consider Influencing Factors. *Procedia CIRP*, 233-238.

Elaad. (2017, november). *Marktverkenning elektrische bussen.* Retrieved from Elaad: https://www.elaad.nl/uploads/downloads/downloads_download/ElaadNL_Marktverkenning_Elektrische_Bussen_november_2017.pdf

Ellen Macarthur Foundation. (2013). Retrieved from https://www.ellenmacarthurfoundation.org/publications/towards-the-circular-economy-vol-1-an-economic-and-business-rationale-for-an-accelerated-transition

European Commission. (2017b). *Study on the review of the list of critical raw materials.* Retrieved from Publications Office of European Union.

European Commission. (2018). *Report on Raw Materials for Battery Applications.* Brussels: European Commission.

Gaines, L., Sullivan, J., Burnham, A., & Belharouak, I. (2011). Life-cycle analysis for lithium-ion battery production and recycling. *Transportation Research Board 90th Annual Meeting, Washington, DC*, 23-27.

Genovese, A., Acquaye, A. A., Figueroa, A., & Koh, S. L. (2017). Sustainable supply chain management and the transition towards a circular economy: Evidence and some applications. *Omega*, 344-357.

Golinska, P., & Hajdul, M. (2012). *Sustainable transport.* Berlin Heidelberg: Springer.

Hawkins, T. R., Gausen, O. M., & Strømman, A. H. (2012). Environmental impacts of hybrid and electric vehicles—a review. *The International Journal of Life Cycle Assessment, 17(8)*, 997-1014.

Hawkins, T. R., Singh, B., Majeau-Bettez, G., & Stromman, A. H. (2013). Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. *Journal of Industrial Ecology*, 53-64.

Hesse, H. C., Schimpe, M., Kucevic, D., & Jossen I., A. (2017). Lithium-Ion Battery Storage for the Grid—A Review of Stationary Battery Storage System Design Tailored for Applications in Modern Power Grids. *Energies*.

Hill, C. (2009). Transportation and sustainability best practices background. *Proceedings, AASHTO Sustainability Peer Exchange*, 32.

Interprovinciaal Overleg. (2015). *Visie Duurzaam Regionaal OV.* Arnhem: IPO.

Kühtz, S., Zhou, C., Albino, V., & Yazan, D. M. (2010). Energy use in two Italian and Chinese tile manufacturers: a comparison using an enterprise input–output model. *Energy, 35(1)*, 364-374.

Lajunen, A. (2014). Energy consumption and cost-benefit analysis of hybrid and electric city buses. *Transportation Research Part C: Emerging Technologies*, 1-15.

Lajunen, A. (2018). Lifecycle costs and charging requirements of electric buses with different charging methods. *Journal of cleaner production, 172*, 56-67.

Lajunen, A., & Lipman, T. (2016). Lifecycle cost assessment and carbon dioxide emissions of diesel, natural gas, hybrid electric, fuel cell hybrid and electric transit buses. *Energy, 106*, 329-342.

Leontief, W. W. (1936). Quantitative input and output relations in the economic systems of the United States. *The review of economic statistics*, 105-125.

Leontief, W., & Ford, D. (1970). Environmental repercussions and the economic structure: an input-output approach. *Review of economics and statistics*, 262-271.

Li, W., Stanula, P., Egede, P. K., & Herrmann, C. (2016). Determining the main factors influencing the energy consumption of electric vehicles in the usage phase. *Procedia Cirp, 48*, 352-357.

Marra, F., Yang, G. Y., Træholt, C., Larsen, E., Rasmussen, C. N., & & You, S. (2012). Demand profile study of battery electric vehicle under different charging options. *IEEE Power and Energy Society General Meeting*, (pp. 1-7).

Messagie, M. (2014). Life Cycle Analysis of the the Climate Impact of Electric Vehicles. *Journal of Life Cycle Assessment*.

Ministerie van Infrastructuur en Milieu. (2019, Januari 28). *Visie Duurzame Brandstoffenmix.* Retrieved from Sociaal Economische Raad (SER).

Mintz, S. M. (2011). Triple bottom line reporting for CPAs. *The CPA Journal*, 26-33.

Nitta, N., Wu, F., Lee, J. T., & Yushin, G. (2015). Li-ion battery materials: present and future. *Materials today, 18(5)*, 252-264.

Nordelöf, A., Messagie, M., Tillman, A. M., Söderman, M. L., & Van Mierlo, J. (2014). Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment? *The International Journal of Life Cycle Assessment, 19(11)*, 1866-1890.

Notter, D. A., Gauch, M., Widmer, R., Wager, P., Stamp, A., Zah, R., & Althaus, H. J. (2010). Contribution of Li-ion batteries to the environmental impact of electric vehicles.

Olivetti, E. A., Ceder, G., Gaustad, G. G., & Fu, X. (2017). Lithium-Ion Battery Supply Chain Considerations: Analysis of Potential Bottlenecks in Critical Metals. *Joule*, 229-243.

Omar, N., Monem, M., Firouz, Y., Salminen, J., Smekens, J., Hegazy, O., . . . Van Mierlo, J. (2014). Lithium iron phosphate based battery–assessment of the aging parameters and development of cycle life model. *Applied Energy, 113*, 1575-1585.

Polenske, K. (2001). Competitive advantage of regional internal and external supply chains. *CONTRIBUTIONS TO ECONOMIC ANALYSIS, 249*, 261-286.

Qnovo. (2016, januari 26). THE COST COMPONENTS OF A LITHIUM ION BATTERY.

Rangaraju, S., De Vroey, L., Messagie, M., Mertens, J., & Van Mierlo, J. (2015). Impacts of electricity mix, charging profile, and driving behavior on the emissions performance of battery electric vehicles: A Belgian case study. *Applied Energy, 148*, 496-505.

Rijksoverheid. (2019, januari 28). *Wat is het doel van het klimaatakkoord?* Retrieved from Klimaatakkoord.

Rogge, M., Wollny, S., & Uwe Sauer, D. (2015). Fast Charging Battery Buses for the Electrification of Urban Public Transport— A Feasibility Study Focusing on. *Energies*, 4587-4606.

Rothgang, S., Rogge, M., Becker, J., & Sauer, D. (2015). Battery design for successful electrification in public transport. *Energies, 8(7)*, 6715-6737.

SER. (2019, januari 28). *Presentatie Zero Emissie Busvervoer: TCO als de kern van de transitie naar zero emissie busvervoer.* Retrieved from energieakkoordser: https://www.energieakkoordser.nl/~/media/files/energieakkoord/nieuwsberichten/2016/20160217-vergadering/presentatie-ser-tcomodelszeb.ashx

Seuring, S., & Müller, M. (2008). From a literature review to a conceptual framework for sustainable supply chain management. *Journal of Cleaner Production*, 1699-1710.

Sinhuber, P., Rohlfs, W., & Sauer, D. U. (2012). Study on power and energy demand for sizing the energy storage systems for electrified local public transport buses. *2012 IEEE Vehicle Power and Propulsion Conference*, (pp. 315-320).

Slaper, T. F., & Hall, T. J. (2011). The Triple Bottom Line: What Is It and How Does It Work? *Indiana business review*, 4-8.

Sustainability, D., Survey, B. G., BRGM, & TNO. (2017). *Study on the review of the list of Critical Raw Materials.* Brussels: European Commission.

The PowerTech Systems Company. (2019, April). *Lithium Iron Phosphate (LFP or LiFePO4) :.* Retrieved from Powertechsystems: https://www.powertechsystems.eu/home/tech-corner/lithium-iron-phosphate-lifepo4/

Thierry, M., Salomon, M., Van Nunen, J., & Van Wassenhove, L. (1995). Strategic issues in product recovery management. *California Management Review*, 114-137.

TNO. (2015). *Inzetbaarheid van zero emissie bussen in Nederland.* TNO. Retrieved from TNO.

Travesset-Baro, O., Rosas-Casals, M., & Jover, E. (2015). Transport energy consumption in mountainous roads. A comparative case study for internal combustion engines and electric vehicles in Andorra. *Transportation Research Part D: Transport and Environment, 34*, 16-26.

Vervoerregio Amsterdam. (2018). *Addendum - Duurzaam OV in de Vervoerregio Amsterdam.*

Walker, S. B., Young, S. B., & Fowler, M. (2015). Repurposing electric vehicle batteries for energy storage to support the smart grid. 4.

Wolfram, A., & Lutsey, N. (2016). Electric Vehicles: Literature Review of Technology Costs and Carbon Emissions. *The International Council on Clean Transportation*, 1-23.

Xu, B., Ulbig, A., Oudalov, A., Andersson, G., & Kirschen, D. S. (2016). Modeling of Lithium-Ion Battery Degradation for Cell Life Assessment. *IEEE Transactions on Smart Grid*, 1131-1140.

Xylia, M., Leduc, S., Laurent, A. B., Patrizio, P., Van Der Meer, Y., Kraxner, F., & Silveira, S. (2019). Impact of bus electrification on carbon emissions: The case of Stockholm. *Journal of Cleaner Production, 209*, 74-87.

Younes, Z., Boudet, L., Suard, F., Gérard, M., & Rioux, R. (2013). Analysis of the main factors influencing the energy consumption of electric vehicles. *In 2013 international electric machines & drives conference*, (pp. 247-253).

ZeEUS. (2017). *ZeEUS.* Retrieved from Zeeus-report2017-2018-final: http://zeeus.eu/uploads/publications/documents/zeeus-report2017-2018-final.pdf

Zhou, L., Li, J., Li, F., Meng, Q., Li, J., & Xu, X. (2016). Energy consumption model and energy efficiency of machine tools: a comprehensive literature review. *Journal of Cleaner Production, 112*, 3721-3734.

# Appendix A: Zero-emission buses in the Netherlands

| Wanneer | Aantal | Type | Techniek | Waar | Vervoerder |
|---|---|---|---|---|---|
| Verschillend | 39 | Hess trolley | Trolley 18m | Arnhem | Breng |
| 2013, april | 6 | BYD | Plug-in 12m | Schiermonnikoog | Arriva |
| 2013, december | 3 | Optare Solo EX | Plug-in 10m | Utrecht | Qbuzz |
| 2014, voorjaar | 4 | Volvo | Plug-in 12 m | Den Bosch | Arriva |
| 2016, juli | 1 | Hymove / Solbus | H2 12m | Apeldoorn | Syntus |
| 2016, december | 4 | VDL Citea SLFAe | OC 18m | Maastricht | Arriva |
| | 12 | VDL Citea LLE | OC 9,9m | Venlo | Arriva |
| | *35* | *BYD* | *Plug-in 12m* | *Schiphol (Airside)* | *SNBV* |
| | 43 | VDL Citea SLFAe | OC 18m | Eindhoven e.o. | Hermes |
| 2017, januari | 11 | VDL Citea SLFe | OC 12m | Vlieland, Terschelling, Ameland | Arriva |
| 2017, februari | 2 | Ebusco HV LE | Plug-in 12m | Groningen | Qbuzz |
| 2017, maart | 3 | VDL Citea SLFe | OC 18m | Terschelling, Ameland | Arriva |
| 2017, mei | 2 | VDL / APTS Phileas | H2 18m | Eindhoven | Hermes |
| 2017, juli | 3 | Iveco Rosero first | Plug-in midi | Dordrecht | Arriva |
| | 2 | VDL Citea LLE | OC 9,9m | Gorinchem | Arriva |
| 2017, augustus | 10 | Ebusco | Plug-in 12m | Utrecht | Qbuzz |
| | 2 | Van Hool | H2 12m | Rotterdam | RET |
| 2017, december | 8 | BYD K9 | Plug-in 12m | Haarlem IJmond | Connexxion |
| | 10 | VDL Citea SLFAe | OC 18m | Groningen | Qbuzz |
| | 2 | Van Hool | H2 12m | Groningen | Qbuzz |
| | 2 | BYD | Plug-in 12m | Amersfoort | Syntus |
| 2018, februari | 7 | BYD | Plug-in 12m | Almere | Keolis NL |
| 2018, april | 9 | VDL Citea SLFe | OC 12m | Den Bosch | Arriva |
| 2018, april | 100 | VDL Citea SLFAe | OC 18m | Amstelland Meerlanden | Connexxion |
| 2018, voorjaar | 8 | BYD | Plug-in 12m | Haarlem IJmond | Connexxion |
| 2018, juni | 4 | Nnb | H2 12m | HWGO | Connexxion |
| 2018, juli | 21 | BYD | Plug-in 8,75m | Noord-Holland Noord | Connexxion |
| | 62 | VDL Midcity Electric | Plug-in midi | Noord-Holland Noord | Connexxion |
| | 10 | VDL SLFA-e 180 | OC 18m | Waterland | EBS |
| 2018 | 2 | Hess trolley | IMC 18m | Arnhem | Breng |
| 2018 | 5 | VDL Citea LLE 99 | Plug-in midi | Zaanstreek | Connexxion |
| 2018, december | 37 | Ebusco 2.1 LF-HV-300 | Plug-in 12m | Dordrecht | Qbuzz |
| | 3 | Iveco Resero First | Plug-in midi | Dordrecht | Qbuzz |
| 2018? | 5 | VDL Citea SLF-120* | OC 12m | Den Haag | HTM |
| **Totaal t/m 2018** | **477** | | | | |
| **Verwacht na 2018** | | | | | |
| 2020 | 31 | Aanbesteding | OC 12m | Amsterdam | GVB |
| 2020 | 55 | Aanbesteding | Nnb | Rotterdam | RET |
| 2020 | 50 | Aanbesteding | H2(RE) 12m | Groningen (20), Zuid-Holland (20), Noord-Brabant (10) | Nnb |
| 2021 | 150 | VDL Citea SLFA-e 210 (ontwikkeling) | OC 21m | AML R-net | Connexxion |
| Tot 2021 | ~60 | Nnb | Nnb | Haarlem-Ijmond | Connexxion |

*Figure 42 Overview of zero-emission buses in the Netherlands (Vervoerregio Amsterdam, 2018); Trolley = trolleybus, Plug-in = plug-in bus, OC = opportunity charging bus, IMC = in-motion charging bus, H2 = hydrogen bus, H2RE = electric bus with hydrogen range extender, Nnb = not known yet*

# Appendix B: Stakeholders in the supply chain

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Concession provider / government | Construct a plan | Tendering | | | | Application of grants | | Carry passenger |
| Concession holder / transporter | | Request information | Construct a plan | Send Tender application | Winning of tender | | | |
| Bus supplier | | Provide information | | | Receive orders | Supply buses | | |
| Charging infrastructure | | Provide information | | | Receive orders | Supply infrastructure | | |
| Fleet monitoring | | Provide information | | | Receive orders | Supply fleet software | | |
| Grid operator | | Provide information | | | Receive orders | Realize connections | Make contract | |
| Energy | | Provide information | | | Receive orders | | Make contract | |
| Passenger organizations | Offer advice | | Offer advice | | | | | Test transport |

*Figure 43 Current course of concession granting and application of charging infrastructure*

# CONFIDENTIAL Appendix C: Bus schedules

# Appendix D: Expected cycle life of $LiFePO_4$ battery cells

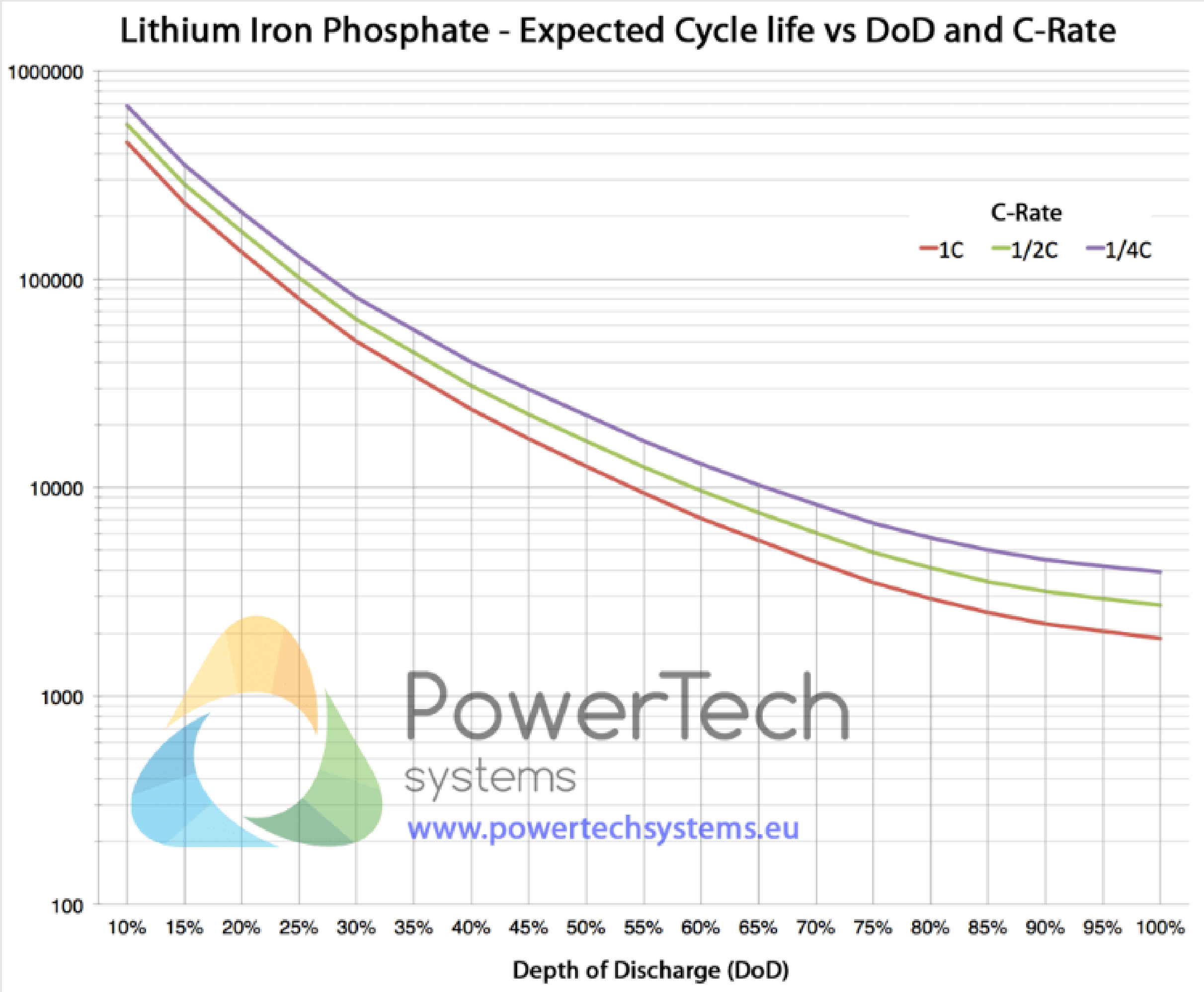



*Figure 47: Lithium Iron Phosphate Life Cycle (The PowerTech Systems Company, 2019)*

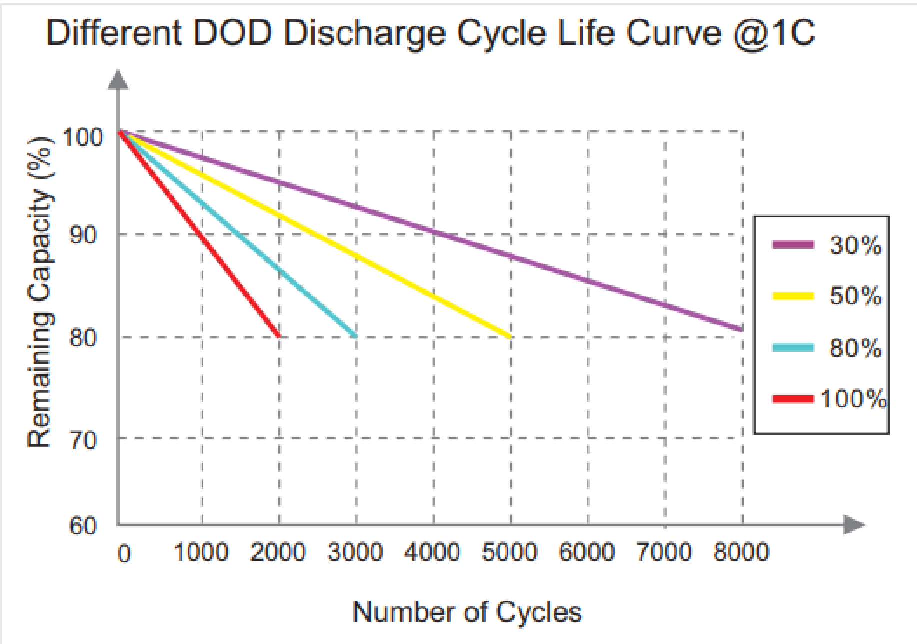



*Figure 48 Cycle life curve (Batteryspace.com, 2019)*

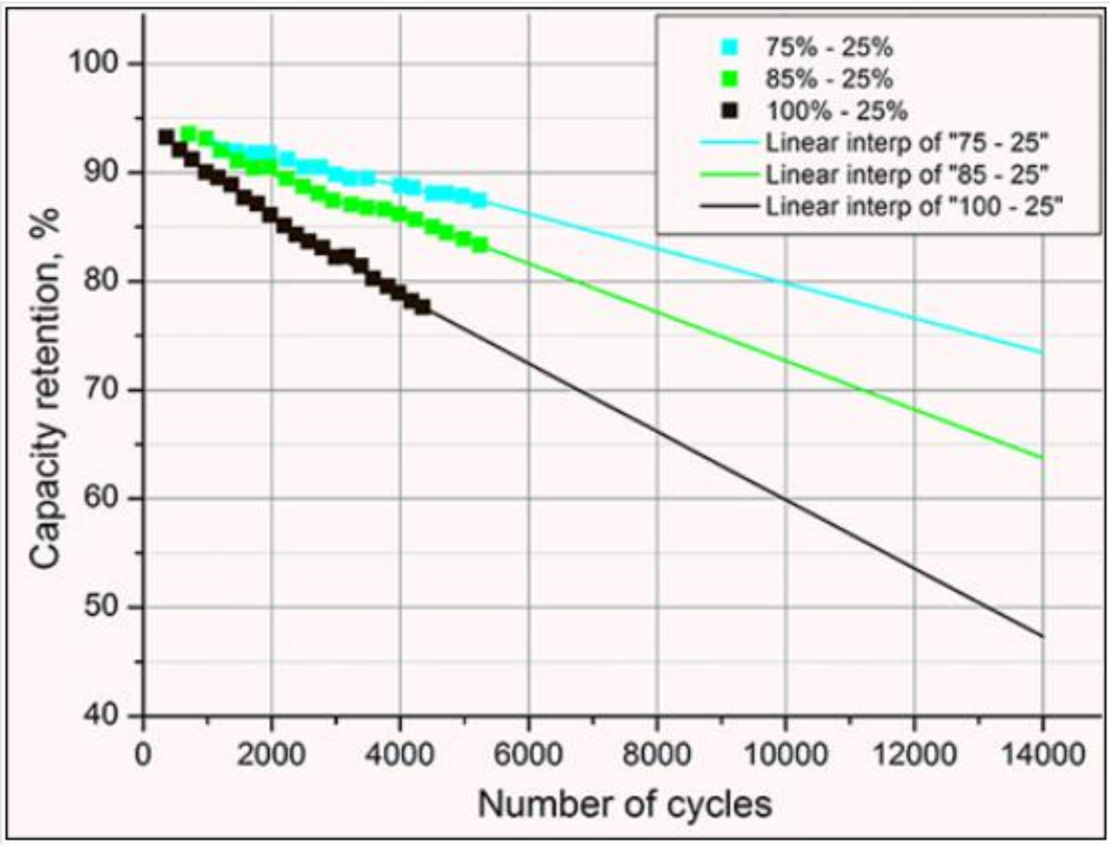



*Figure 49 Predictive modeling of battery life by extrapolation (Battery University, 2019)*

# CONFIDENTIAL Appendix E: Assumptions in the scenarios