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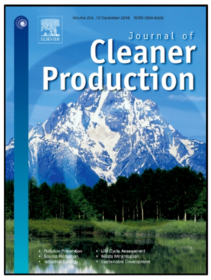


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# Impact of bus electrification on carbon emissions: the case of Stockholm

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## 1. Introduction

The Conference of the Parties to the UNFCCC (COP 21) held in December 2015 in Paris resulted in a historical agreement among 195 countries to reduce greenhouse gas (GHG) emissions and limit global temperature increase to 2 degree Celsius (see e.g., European Commission, 2016). Cities will play an important role in this context. In fact, urban regions accounted for 64% of global primary energy use and 70% of carbon emissions in 2013 (IEA, 2016).

One of the major challenges to achieve environmental sustainability in cities is the decarbonization of transport. The transport sector emissions represented 23% of the global emissions in 2013, with road transport emissions accounting for 75% of the total emissions in the sector (IEA, 2015). By 2013, emissions from road transport had increased by 68% compared to 1990 (IEA, 2015). Electrification of road transport in combination with a modal shift towards public transport can be key to achieving decarbonization and energy efficiency improvement of the sector (Creutzig et al., 2015). In line with the above, Sweden has been testing solutions for bus transport electrification in various locations around the country. Electricity is one of the most attractive fuel options for Swedish public bus fleets, according to a survey among environmental managers of the Public Transport Authorities (PTAs) (Xylia and Silveira, 2017). A target of 80% electric city buses by 2030 and 100% by 2050 is suggested by the Swedish government (Regeringskansliet, 2013).

To make sure these solutions lead to lower carbon emissions, the climate change impact needs to be quantified. Different compositions of the electricity mix lead to different levels of carbon emissions, which needs to be accounted for. Furthermore, it is important to assess the impact of the components that are necessary for electrification, such as the batteries, over their whole life cycle. In order to quantify such impacts and compare them with other existing fuel alternatives, this study uses Life Cycle Assessment (LCA) (ISO, 2006) to quantify life cycle climate change impacts. LCA has the advantage of assessing the whole life cycle of a product, thereby avoiding shifting an impact from one stage to another in the life cycle (Jolliet et al., 2015).

The representation of life cycle carbon emissions in this paper is an enhancement of the model for electric bus network optimization originally presented in Xylia et al. (2017a). The model was applied to the city of Stockholm, Sweden. The main questions we aim to answer in this paper are the following: *(i)* How does *large-scale electrification affect the life cycle carbon emissions of the Stockholm bus network and how does it compare to the use of other fuels? (ii) How do battery characteristics (e.g., capacity, specific energy) affect the environmental impact of electric buses? and (iii) What is the impact of bus electrification in terms of reduction of air pollutants in Stockholm's inner city?* The overarching objective of the study is to quantify the climate change impact of bus transportation using different fuels, further elaborating on aspects such as battery impact on emissions as well as the impact of bus electrification on local air quality.

We measure the impact of emissions in carbon dioxide equivalents ($CO_{2eq}$), which translates all emissions into carbon equivalents and derive the global warming potential (GWP) for a given mixture of greenhouse gases. Other life cyle impact categories, such as eutrophication, human toxicity and acidification potentials are not included in this study. In addition to the reduction of greenhouse gas emissions, electrification of urban transportation can help to reduce pollutant emissions in the inner city, such as particulate matter (PM) and Nitrogen Oxides (NOx). Therefore, the study includes a local assessment of the potential local reduction of the above mentioned pollutants as a result of bus electrification. The emissions factors used are based on Stockholm specific data, and we compare available bus technologies during the use phase in bus transport.

Following the present introduction, Section 2 presents the literature review on this research topic, and highlights the contribution of this study. Section 3 presents the data and methods applied in the study. Section 4 presents the results, answering the three key questions related to the carbon emissions of a partially electrified bus network, the implications of different battery sizes, and the impacts of electrification on Stockholm's inner city in particular. Finally, conclusions on the study and future research directions are given in Section 5.

## 2. Literature review

Life cycle carbon emissions associated with public bus operation have been previously investigated in several studies. Chan et al. (2013) use the LCA methodology to assess greenhouse gas emissions along a busy transit corridor in Montreal, Canada. Different powertrain technologies (compressed natural gas, biodiesel and diesel electric hybrid) are compared using the *GHGenius* life cycle tool (Natural Resources Canada) and *Motor Vehicle Emission Simulator* (by USEPA) to simulate various speed scenarios. The authors conclude that emissions related to fuel consumption of the bus account for the largest share of life cycle emissions.

Lajunen and Lipman (2016) evaluate life cycle costs, energy consumption, and emissions of diesel, natural gas, hybrid electric, fuel cell hybrid and battery electric city buses. Hybrid buses have both an internal combustion engine and an electric engine or fuel cells. The results indicate significant emissions reduction for hybrid and electric buses compared to conventional fossil fueled buses. Energy consumption is calculated using the *Autonomie* vehicle simulation model for various types of operating cycles. Emissions associated with bus operation and fuel production in Finland and California are considered.

Dreier et al. (2018) estimated Well-to-Wheel (WTW) fossil energy use and greenhouse gas (GHG) emissions for six types of city buses in the city of Curitiba, Brazil, including conventional, hybrid-electric and plug-in hybrid-electric powertrains. The operation phase (Tank-to- Wheel, TTW) of the city buses was simulated using the Advanced Vehicle Simulator (ADVISOR) software. The study showed hybrid-electric and plug-in hybrid-electric two-axle city buses consuming 30% and 75% less WTW fossil energy per distance compared to a conventional two-axle city bus. This leads to a 27% reduction of WTW GHG emissions when a plug-in hybrid vehicle is used compared to a conventional city bus (1115 g$CO_{2eq}$ /km compared to 1539 g $CO_{2eq}$ /km for the conventional bus).

Mahmoud et al. (2016) present a holistic review of alternative powertrain technologies including economic, environmental, operational, and energy efficiency aspects. Hybrid electric, fuel cell and battery electric buses are compared to diesel buses. The authors conclude that, although the performance of electric buses is sensitive to energy profiles and operational demands, the battery electric buses that use electricity from renewable sources are the best option when considering environmental benefits and operational advantages. The authors also highlight the correlation of emission reduction potential from electric buses to the electricity mix used, i.e., emission reduction differs depending on the national electricity mixes considered, an issue that is also analyzed in the present study.

García Sánchez et al. (2013) highlight the impact of the electricity mix on life cycle emissions from electric buses, exploring the case of Spain. The study presents a global LCA for a fuel cell hybrid bus, a hybrid diesel electric bus, a battery electric bus and an internal combustion bus. The analysis shows an estimated 1670 g$CO_{2eq}$/km for the diesel bus in the year 2010, which is two times higher than the LCA value estimated for the battery electric bus (790 g$CO_{2eq}$/km). Future shifts towards renewables in the Spanish electricity mix will lead to reduced emissions associated with battery electric buses.

Another study highlighting the impact of the electricity mix on the environmental effects of electric buses was done for Macau, China (Song et al., 2017). The authors conclude that, under current conditions and considering charging and distribution losses, electric bus emissions would exceed emissions of conventional diesel buses. Another case study for Macau quantifies the impact of electric bus use in terms of the amount of local pollutants. More specifically, battery electric buses can reduce

WTW emissions of $NO_x$ and Volatile Organic Compounds (VOC) by 60 to 80%, compared to a EURO IV diesel bus (He et al., 2018).

Other studies, such as Durango-Cohen and McKenzie (2017) and McKenzie and Durango-Cohen (2012), present LCA results for various powertrain technologies. However, battery electric buses are not part of their analyses, and only hybrid electric buses are considered. Abdul-Manan (2015) discusses the uncertainty of LCAs for electric vehicle emissions. Although not directly analyzing buses, the results offer valuable insights for the comparison between battery electric vehicles and internal combustion engine vehicles. The difference in greenhouse gas emission reduction between the two powertrain technologies is 43% in average, with a 95% confidence interval.

The uncertainty of estimations of emissions indicated in various studies should always be kept in mind. The uncertainties surrounding emission assessments do not only originate from the LCA methodology per se. Uncertainties are also linked to the chosen methodological approach within the LCA including, for example, details of the electricity mix, marginal emissions or EU-ETS (EU Emissions Trading System) argumentation among others (see Ensslen et al., 2017; Jochem et al., 2015).

From the studies discussed above, we gather that different assumptions, differences in powertrain characteristics and driving cycles, as well as diverse fuel mixes used around the world influence the greenhouse gas emissions in each system. In other words, the actual emissions can vary significantly from one city to another entailing specific analysis before policies and actions are defined.

This study contributes to this field of knowledge by analyzing the emissions from various fuels and electricity mixes with an optimization model aimed at determining the location of bus charging infrastructure. In this way, one can observe impacts of electrification at larger-scale, i.e. for large bus networks. Emissions can be estimated for specific scenarios of infrastructure deployment, thus serving to guide the deployment of electric vehicles, for example, along with the transformation of energy mixes. In addition, optimal configurations for fuel choices, battery capacities and charging locations for electric public transport, and their cost-related implications can be determined.

## 3. Methodology

This section presents the methodology used to obtain the minimization of the carbon emissions of bus transport applied to the city of Stockholm. It is composed of two parts: the life cycle assessment to quantify greenhouse gas emissions, and the optimization model. As mentioned earlier, this optimization model is a new, expanded version of the model used in Xylia et al. (2017a). Here, the model component estimating emissions is enhanced with more detailed calculations for fuel-associated emissions and vehicle battery-associated emissions of the bus network selected. The objective of the study is to quantify the climate change impact of bus transportation using different fuels, as well as the battery impact in case electric buses are used.

### 3.1 Life cycle assessment to calculate carbon emissions

A comparative life cycle assessment (LCA) in line with the ISO 14044 standard (ISO, 2006) is used. The lifecycle impact of the powertrain and its maintenance, the road construction and the actual transportation service delivery have been excluded from the analysis, as they are considered to have similar impact regardless of the engine technology and fuel used. Additionally, according to previous literature, their impact on the total life cycle emissions is relatively low when compared to the impact of fuels or batteries. For example, diesel and electric hybrid powertrains have the same total vehicle cycle emissions, which is 8.5% of the total upstream emissions according to Chan et al. (2013), while the share of emissions from the chargers has been found to be even lower, that is, at around 1% according to Bi et al. (2015). However, the specific design and sizing of each charger could potentially affect these values.

In this study, the carbon emissions of the various fuels and of the batteries were analyzed separately as described in the following sections.

### 3.1.1 Fuel emissions

The common functional unit used for the different fuels analysed is one kWh. The four alternatives included in this study, i.e. Hydrotreated Vegetable Oil (HVO), Fatty Acid Methyl Ester (FAME), certified renewable electricity and the Nordic electricity mix were modeled in *Simapro V8.4* (Pré, 2016). SimaPro is a widely used LCA software for modelling and analyzing life cycles in a systematic way. The software analyses environmental impact of products and services across all the stages of their life cycle, such as manufacturing, distribution, use, and disposal. The *ecoinvent v3.2* database (ecoinvent Centre, St Gallen, Switzerland) was used for background data. Ecoinvent is a Life Cycle Inventory (LCI) database which includes data on the life cycle environmental impact of various products and process in the areas of energy supply, agriculture, transport, biofuels, chemicals etc.

The carbon emissions were calculated with the IPCC 2013 GWP 100-year method (IPCC, 2007). The primary data for the biofuels were based on information published by the Swedish Energy Agency (2016), while data for the annual average electricity mix were extracted from information published by the IEA and Nordic Energy Research (2016). The estimation of life cycle emissions for biofuels is reported by the Swedish Energy Agency according to the Annex V of the EU Renewable Energy Directive (RED) (European Parliament, 2009) (see Table 1). The emissions reported are Well-to-Wheel (WTW), which means that the whole life cycle of the fuel is covered, from feedstock recovery to finished fuel and the combustion of the fuel in the engine. We compare the emissions factors reported by the Swedish Energy Agency with the LCA model results as shown in Table 1. The comparison shows small differences between our estimations and the literature for the case of HVO and the Nordic electricity mix, while somehow larger differences occur for the case of FAME and certified renewable electricity. For the case of FAME, the LCA model estimates lower emission factors (-17%) than the literature, while for certified electricity the model values are 32% higher than the available data for a Swedish case of electricity from renewable sources.

**Table 1: Emission factors for the fuels considered in the analysis (2015 values)**

| Fuel | Emission factor literature (g $CO_{2eq}$/kWh) | Emission factor calculated in LCA model (g $CO_{2eq}$/kWh) | Comparison literature vs. LCA model (in %) |
|---|---|---|---|
| Hydrotreated Vegetable Oil (HVO) | 43[1] | 39.6 | -8% |
| Fatty Acid Methyl Ester (FAME) | 140[1] | 116 | -17% |
| Certified renewable electricity | 9[2] | 11.9 | 32% |
| Nordic electricity mix | 124 [1] | 136 | 10% |

[1]*Swedish Energy Agency (2016)*
[2] *Vattenfall (2017)*

HVO is modeled in *Simapro*, based on *ecoinvent* data for an estimated mix of rapeseed oil (11%), vegetable and animal oil residues (32%), slaughterhouse residues (29%), palm oil (14%) and crude tall oil (14%), with information from the statistics for 2015 (Swedish Energy Agency, 2016a). The raw tall oil is mainly produced in Sweden, with a small amount coming from Finland and the USA (5% and 3%, respectively) (Swedish Energy Agency, 2016a). The slaughterhouse residues originate generally from other EU countries, and the same is true for vegetable and animal oil residues. The rapeseed oil originates mainly from EU countries, with a smaller share originating from Australia and Russia (10% and 7%, respectively) (Swedish Energy Agency, 2016a). HVO imports by country are illustrated in Figure 1. Defining the origin of the fuels in use is crucial for the accuracy of the emissions analysis in the LCA.

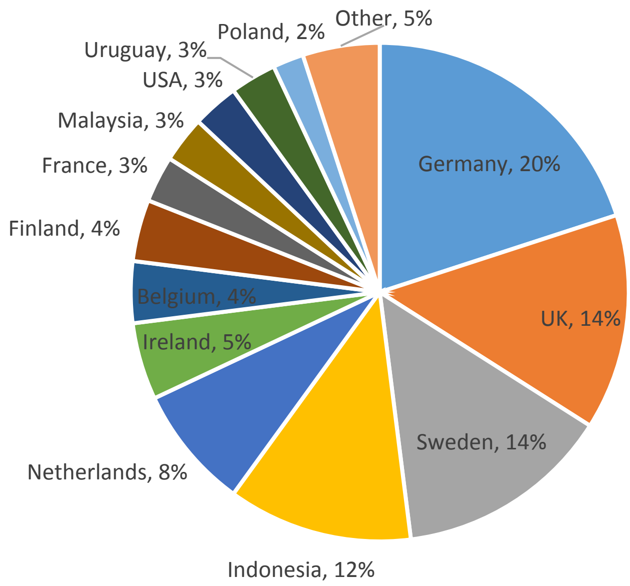



**Figure 1: Origin of HVO imports to Sweden (data extracted from Swedish Energy Agency, 2016) (Note: Other includes Austria, Lithuania, Australia, Denmark, Spain, Romania, Italy, Slovakia, Russia, Latvia and Belarus (in order of importance))**

FAME has been in the market longer time than HVO. Both FAME and HVO are renewable fuels that can substitute fossil diesel. In Sweden, all FAME is produced from rapeseed oil (RME). One of the reasons why RME is commonly used is that it gives the biodiesel attributes that can withstand the cold Nordic climate (Swedish Energy Agency, 2016a). FAME imports by country are illustrated in Figure 2.

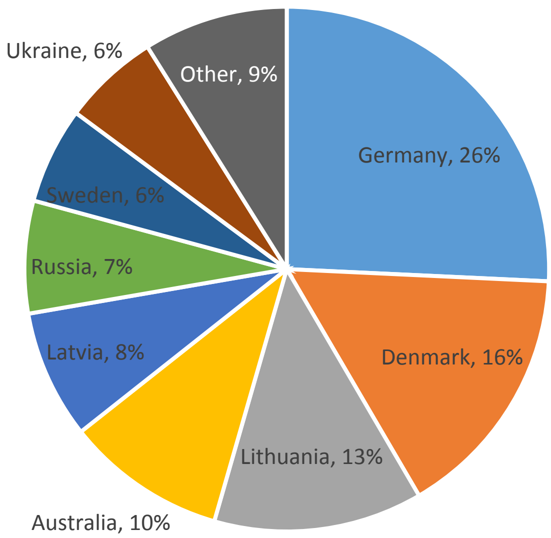
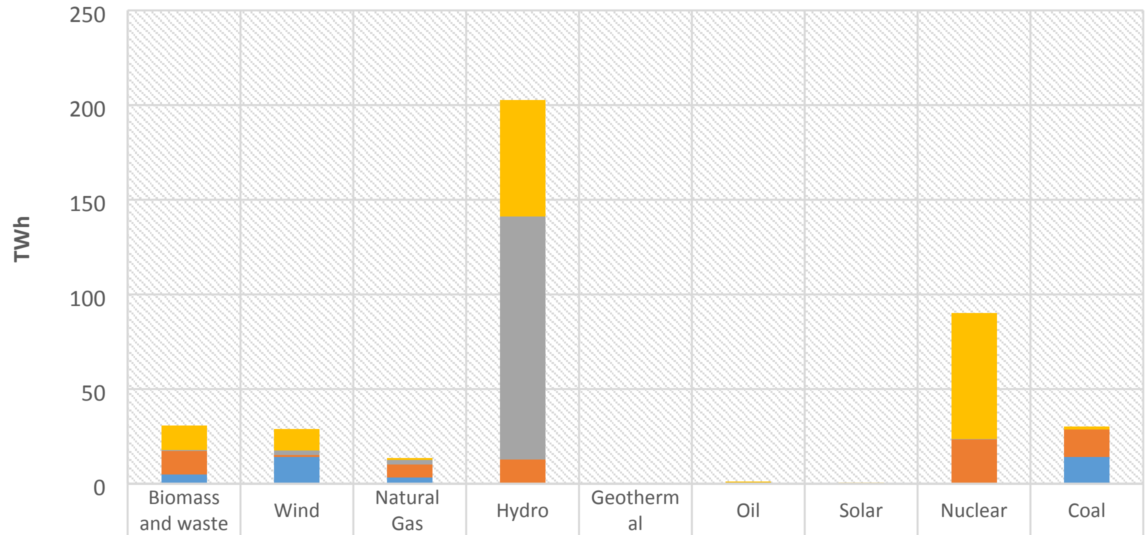



**Figure 2: Origin of FAME imports to Sweden, 2015 (data extracted from Swedish Energy Agency, 2016) (Note: Other includes (from higher to lowest share) UK, Romania, France, Poland, Belarus, Czech Republic, Hungary, Paraguay and Netherlands)**

Electricity, unless certified as renewable electricity, is assumed to have the characteristics of the Nordic mix based on data for the electricity generation per Nordic country for the year 2013 (see Figure 3). The share of each primary energy source in the mix is illustrated in Figure 4. Certified electricity is modelled as "BraMiljöval" electricity ("*green electricity*"), i.e. assumed to originate from hydropower (95%) and wind (5%) (Vattenfall, 2017). It should be noted that, as both the electricity mix composition and origin of the fuel changes over time, there can be differences in the emission factors from year to year.

The biggest impact on the emissions of the Nordic electricity mix is coming from the use of coal in Denmark and Finland. Both countries have announced their plans to phase out coal plants by 2030. This would reduce the emissions of the electricity mix even further and enhance the benefits on emission reduction from transport electrification.




| | Biomass and waste | Wind | Natural Gas | Hydro | Geothermal | Oil | Solar | Nuclear | Coal |
|---|---|---|---|---|---|---|---|---|---|
| Sweden | 12.74 | 11.18 | 0.84 | 61.36 | 0.00 | 0.41 | 0.04 | 66.46 | 1.35 |
| Norway | 0.55 | 2.22 | 2.45 | 128.48 | 0.00 | 0.03 | 0.00 | 0.00 | 0.14 |
| Finland | 12.33 | 1.19 | 6.79 | 12.84 | 0.00 | 0.23 | 0.01 | 23.61 | 14.37 |
| Denmark | 5.05 | 14.20 | 3.40 | 0.01 | 0.00 | 0.35 | 0.52 | 0.00 | 14.29 |

**Figure 3: Electricity generation in the Nordic Countries (TWh), 2013 (data from IEA and Nordic Energy Research, 2016) (Note: Iceland is excluded because the electricity market is not common as its grid is not connected to the other Nordic countries)**

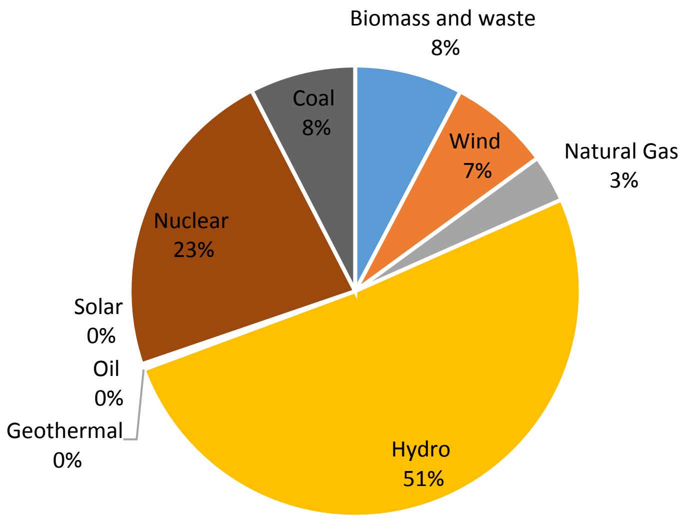


**Figure 4: Nordic electricity composition by primary energy source, 2013 (data from IEA and Nordic Energy Research, 2016) (Note: Iceland is excluded because the electricity market is not common as its grid is not connected to the other Nordic countries)**

### 3.1.2 Batteries' emissions

The LCA on batteries modeled in *SimaPro v8.4* refers to a Li-Ion rechargeable battery as listed in the *Ecoinvent* database *v3.1* (Moreno Ruiz et al., 2014, 2013). The carbon emissions of this battery are calculated with the IPCC 2013 method and are estimated to be 6.19 kg $CO_{2eq}$/kg battery. The specific energy of the battery is assumed to be 80 Wh/kg, in line with previous literature, such as Sinhuber et al. (2012) and Lindgren (2015). Other studies have assumed specific energy values of up to 100 Wh/kg, as for example in Rogge et al. (2015). The specific energy strongly depends on battery chemistry and design and thus the values mentioned above are subject to a sensitivity analysis in Section 4.

The life cycle emissions from batteries have been modelled with an LCA perspective in various studies (Bi et al., 2015; Dunn et al., 2012; Ellingsen et al., 2014; Majeau-Bettez et al., 2011). Due to the various assumptions made in each study, there are uncertainties associated with the results obtained. Nevertheless, such results can serve as an indication and can be used for comparisons to the present analysis. A study recently published by (Romare and Dahllöf, 2017) includes a comprehensive literature review of available LCA studies for batteries used in electric vehicles. Based on this review, the authors conclude that greenhouse gas emissions of 150-200 kg $CO_{2eq}/kWh_{battery}$ correspond well to the current burden of battery production. Assuming the specific energy of the electric bus battery to be 80 Wh/kg, as mentioned earlier, the value of 6.19 kg $CO_{2eq}$/kg battery corresponds to 77.37 kg $CO_{2eq}/kWh_{battery}$ which is approximately half of the median of the range indicated in Romare and Dahllöf (2017). To address such differences, the impact of both the estimated values for battery-associated emissions and the specific energy are considered in the sensitivity analysis in Section 4 of this paper.

The impacts from the battery use phase depend upon vehicle characteristics, drive cycles, and the electricity mix among others, and are excluded from this study. The battery emissions are calculated assuming an average battery lifetime of seven years, as shown in a recent study testing battery degradation in electric buses carried out in Denmark (Norregaard et al., 2016). The depreciation time for vehicles and infrastructure assumed in the model is 15 years. Thus, we take into account one battery replacement during the bus lifetime, with the impacts of this replacement included in the model estimations.

## 3.2 Optimization model

The model optimizes the distribution of charging infrastructure for battery electric buses (electric buses hereafter) in the city, taking into account current fuel alternatives. We combine geospatial analysis in the Geographic Information System (GIS) software ArcGIS, with input data managed with Python programming language, and cost and energy optimization performed in the General Algebraic Modeling System (GAMS). The model is applied to the bus network selected, i.e. the optimization occurs at the system's level and not for each bus route. We argue that there are significant benefits that can be accrued from synergies between the various bus routes. Therefore, an approach where each bus route is individually optimized was not preferred.

The structure of the model can be split in four main components: (i) the *data processing component* where information on the characteristics and costs of the bus and charging station technologies as well as schedules is collected and managed; (ii) the *geospatial component* where bus routes are matched to their respective bus stops and the bus stop distance matrices are extracted; (iii) the *optimization component*, where the objective function is minimized; and (iv) *the scenario analysis component*, where the selected charging stations from the optimization component are located and sensitivity analysis on various parameters is performed.

The data collected fall within the following general categories: costs, technologies, and design-related parameters. When available, Swedish literature was prioritized for selecting the parameter values due to higher relevance to this case study. The infrastructure and vehicle costs are annualized, using a depreciation period of 15 years and discount rate of 5% (SLL, 2015), which is in line with the assumptions made by the Stockholm Public Transport Authority for studies within the same context. It is assumed that no additional infrastructure costs occur for non-electric buses, since the infrastructure is already in place.

The optimization is performed in the model using the package for Mixed Integer Linear Programing (MILP) in the GAMS software using the solver CPLEX (McCarl et al., 2008). The model was initially developed in Xylia et al. (2017a). Here, an additional component focusing on emissions is developed. For more information on the optimization model the reader is referred to Xylia et al. (2017a) and Xylia et al. (2017b). The method for assessing the emissions is an addition to the previously developed model and described in more detail Section 3.3.

We apply energy balances for each station, with the necessary differentiation between start, end, and mid stops, i.e. different equations are applied when the stop is first or last in the route's distance matrix. The dependent variables are the binary variables $\mathrm{US}_{\mathrm{l,s,tech}}$, which indicates the need to install a charger at the stop or not, and $\mathrm{TUS}_{\mathrm{l,s,tech}}$, which associates each bus route with a specific technology (biodiesel or electric). The positive variables of the model are $\mathrm{C}^{\mathrm{total}}$ (the total annual costs), $\mathrm{E}^{\mathrm{total}}$ (the total annual energy consumption), and $\mathrm{U}^{\mathrm{total}}$ (the total annual emissions).

The objective function here is the total costs. The costs include infrastructure, operation and maintenance (O&M), fuel, and vehicle costs for a selected bus network. Together with the costs, energy consumption and emissions (in $CO_{2eq}$) are calculated per bus route using the total number of trips in a year multiplied by the route length.

The values and abbreviations of the parameters used in the equations are listed in Appendix Table A.1 and A.2.

The objective function for the total costs is the following:

$$C_{total} = \begin{cases} \sum_{l=1}^{L}\sum_{s=1}^{S}\sum_{tech=1}^{TECH}(C_{l,tech}^{infrastructure} * US_{l,s,tech}) \\ + \sum_{l=1}^{L}\sum_{tech=1}^{TECH}\left[(C_{l,tech}^{O\&M} + C_{l,tech}^{fuel}) * L_l * TC_l + C_{l,tech}^{vehicle} * N_l^{vehicle} * TUS_{l,tech}\right] \end{cases}$$

**Equation 1: Estimating total costs of the bus network**

The total energy consumption is calculated as follows:

$$E_{total} = \sum_{l=1}^{L}\sum_{tech=1}^{TECH} Cons_{tech} * L_l * TC_l * TUS_{l,tech}$$

**Equation 2: Estimating total energy consumption of the bus network**

## 3.3 Assessment of $CO_2$ emissions

To answer the first and second research question *(how large-scale electrification affects the life cycle carbon emissions of the Stockholm bus network and how battery characteristics affect the environmental impact of electric buses),* the total annual emissions of the bus network are obtained through estimating (i) the *fuel-associated emissions*, using the emission factors of various fuels presented in Section 2.1.1 (see Table 1); and (ii) the *battery-associated emissions*, taking into account the life cycle impact of battery production (see Section 2.1.2). Both components are based on the outputs of the LCA discussed in Section 2.1. With this structure, it is possible to get estimations on the total emissions, as well as the split between fuel and battery emissions. In line with the above, the total emissions of the selected bus network are calculated as follows:

$$U_{total} = \begin{cases} \sum_{l=1}^{L} \sum_{tech=1}^{TECH} (EF_{tech} * Cons_{tech} * L_l * TC_l * TUS_{l,tech}) + \\ \sum_{l=1}^{L} \sum_{tech=1}^{TECH} N_{battery\ change} * (EB_{tech} * Cap_{tech} * \frac{1}{SEB_{tech}} * \frac{1}{Life^{battery}} * N_l^{vehicle}) \end{cases}$$

**Equation 3: Calculation of total annual emissions in the optimization model (assuming one battery replacement during vehicle lifetime, $N_{battery\ change}$ = 2, $Life_{battery}$ = 7)**

We delimit our analysis to fuel and battery emissions, as discussed previously, under the assumption that these two components have the largest impact.

For answering the third research question *(what impact bus electrification has on reduction of air pollutants (PM, $NO_x$) in Stockholm's inner city),* the number of daily trips per bus route based on the schedule data is estimated in the model. The number of daily trips for the inner city bus routes can be thus identified.

The day used for the analysis is a typical Monday in May 2016. The public transport schedule in Stockholm varies depending on the season. The schedule is different during the summer months (less trips and buses used). The schedule also varies between regular work days and weekends. We used therefore a day which was not during the summer schedule months and not during a weekend.

From the schedule, the unique trips can be extracted. When multiplied with each route's length, the total daily bus transport volume (in vehicle kilometers) is obtained. This can be multiplied with the energy consumption per vehicle-kilometer. Statistics published on the Swedish Public Transport Association's database show the average levels of pollutants from Stockholm's buses in 2016 (see Table 2). Assuming the energy consumption per vehicle-kilometer for biodiesel buses, one can estimate the energy savings from electrification. Using the data on pollutants, the avoided exhaust emissions from bus electrification can be estimated. Following from that, the impacts of electrification in the inner city can be estimated.

**Table 2: Statistics on pollutants (in g/km) for Stockholm's bus fleet as of 2016 (Source: Svensk Kollektivtrafik, 2017)**

| Pollutant | average emissions for Stockholm bus fleet, 2016 (g/km) |
|---|---|
| $NO_x$ | 3.64 |
| PM | 0.03 |
| $CO_{2eq}$ | 315 |

# 4. Results and discussion

## 4.1 Cost-optimization model results

The locations considered for installing electric charging stations are: (i) at major public transport hubs; and (ii) at the start and end stops of bus routes . There are in total 480 public bus routes in Stockholm region. Out of them 143 (30% of the total number of routes) pass the 10 largest public transport hubs where terminals for connecting to other public transport means (subway, commuter train, light rail train) are in place. These 143 routes are the routes which are included in the optimization model.

Figure 5 presents the cost-optimization results on the location of chargers, as well as the technology selected for each bus route represented in the model. The results shown here are for a battery capacity of 60 kWh in the electric buses. The cost optimization results indicate that out of the 143 bus routes selected, 91 should operate on biodiesel (HVO) and the remaining 52 are operating on electricity.

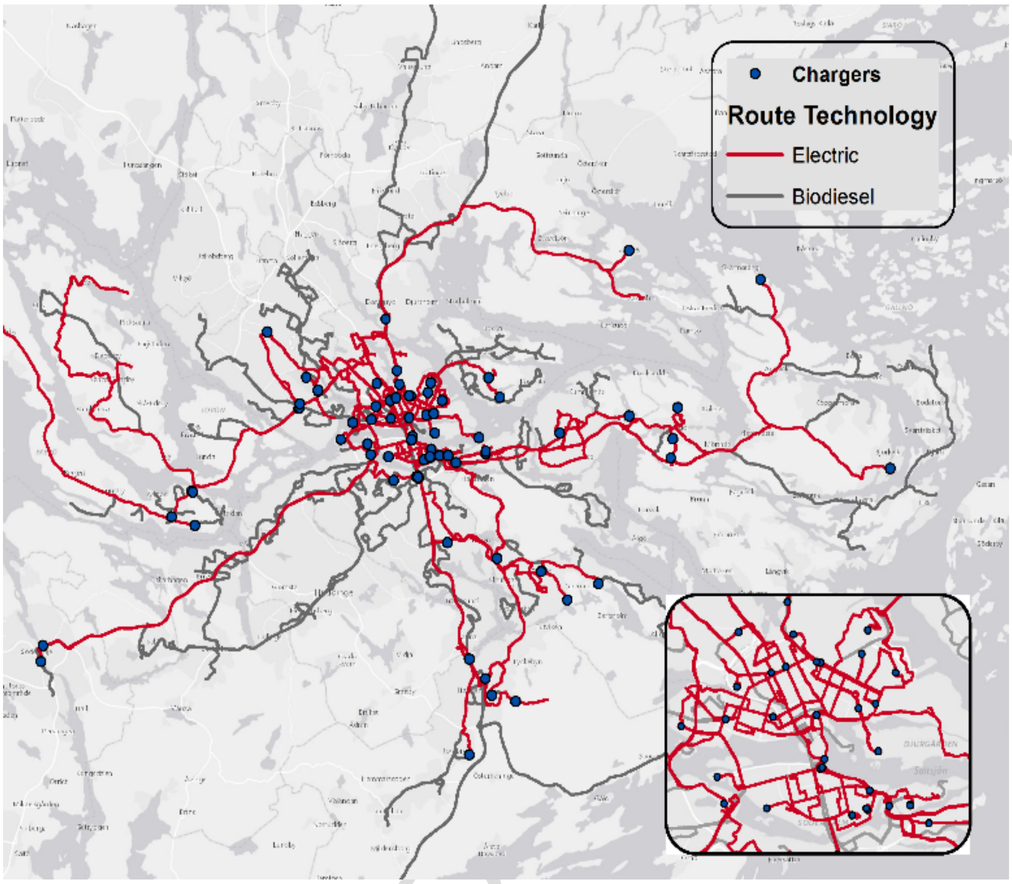



**Figure 5: Bus technology selection and electric bus charging station locations by the cost optimization model (battery capacity of 60 kWh). Map inset shows Stockholm's city in more detail.**

Table 3 presents the results from the cost-optimization model for total annual costs, energy consumption, and emissions as well as a comparison with 100% electricity (certified and Nordic mix) and biodiesel (HVO and FAME). The total annual cost for running the system is 3.70 billion SEK. It should be noted that approximately 65% of the costs are related to operations and maintenance (O&M). This is in line with previous studies for bus transport in Sweden (SKL, 2014; WSP, 2014a, 2014b), that indicate the high impact of O&M costs on public transport costs. The total annual emissions of the selected bus network are estimated at 12.73 kt $CO_{2eq}$/year, with the fuel-associated emissions representing a share of 95% compared to the much smaller share of battery-associated emissions.

**Table 3: Annual costs, energy consumption and emission results from the cost-optimization model in comparison to various fuel alternatives**

| | Cost-optimization results (91 routes with HVO + 52 routes with certified electricity) | All routes with certified electricity | All routes with Nordic electricity mix | All routes with biodiesel (HVO) | All routes with biodiesel (FAME) |
|---|---|---|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| **Costs (billion SEK[1]/year)** | **3.67** | **3.91** | **3.91** | **3.86** | **3.86** |
| *Infrastructure (billion SEK/year)* | *0.02* | *0.07* | *0.07* | *0* | *0* |
| *Operation and Maintenance (O&M) (billion SEK/year)* | *2.70* | *2.74* | *2.74* | *2.58* | *2.58* |
| *Vehicles (billion SEK/year)* | *0.46* | *0.62* | *0.62* | *0.36* | *0.36* |
| *Fuel (billion SEK/year)* | *0.49* | *0.48* | *0.48* | *0.92* | *0.92* |
| **Energy consumption (GWh/year)** | **393** | **320** | **320** | **647** | **647** |
| **Emissions ($ktCO_{2eq}$/year)** | **12.73** | **9.88** | **30.19** | **25.65** | **75.14** |
| *Fuel-associated emissions ($ktCO_2eq$/year)* | *12.03* | *8.15* | *28.46* | *25.65* | *75.14* |
| *Battery-associated emissions ($ktCO_2eq$/year)* | *0.70* | *1.73* | *1.73* | *0* | *0* |

In Figure 6, the total emissions of the bus network using different fuels are shown. This is to highlight the impacts of using specific fuels, and to provide a reference for comparison with the model results. In the latter, a combination of buses running on HVO and electricity is the cost-optimal solution. Using certified renewable electricity for the whole bus network results in the lowest emission impact. This is followed closely by the emissions estimated in the cost-optimization model (52 bus routes electrified, and the remaining routes on HVO, see Section 4.1). The emissions of the cost-optimized bus network are 50% lower than emissions from a bus network running on 100% HVO. The emissions obtained for a system using 100% HVO are in the same range as a system operating on 100% Nordic electricity. The highest emissions are obtained from a 100% FAME system.

It can be noted that, although the Nordic electricity mix has a three times higher emission factor than HVO (see Table 1), it actually leads to total emissions which are comparable to HVO. The reason is that electric buses are more energy efficient and, as a result, the total energy consumption of the bus network is much lower (320 GWh for electricity, 647 GWh for HVO). It is also shown that, from an emissions reduction perspective, a full-electric bus fleet running on the average Nordic electricity mix is not better than a bus fleet running on HVO (see Figure 6). The situation would be even less favorable for electricity mixes in other regions. For example, the EU electricity mix has an emission factor of 565 $gCO_2eq$/kWh, which is about 4.5 times higher than the average Nordic mix emission factor (Covenant of Mayors Office and Joint Research Centre of the European Commission, 2014).

Additionally, there is a large difference between the emission impact of the Nordic electricity mix and the certified renewable electricity mix. This confirms that the origin of the electricity used for the buses is key for the reduction of emissions from the buses. Furthermore, it should be noted that the impact of second generation biofuels, such as HVO, is much lower than their first generation counterparts, such as FAME.

Finally, the results highlight 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 the power plants, wind farms etc., as well as the life cycle impacts of batteries and various components used. The difference in battery-associated emissions, more specifically, makes the electricity and HVO mix proposed for the operation

[1] *SEK is the Swedish currency (Swedish Krona). The average exchange rate for 2017 is 1SEK = 0.095€ (Oanda, 2018)*

of the bus network a compelling option when it comes to emissions reduction for public bus transport operation. The latter requires less investment on new infrastructure than a full electric bus network, but still leads to quite significant emission reductions.

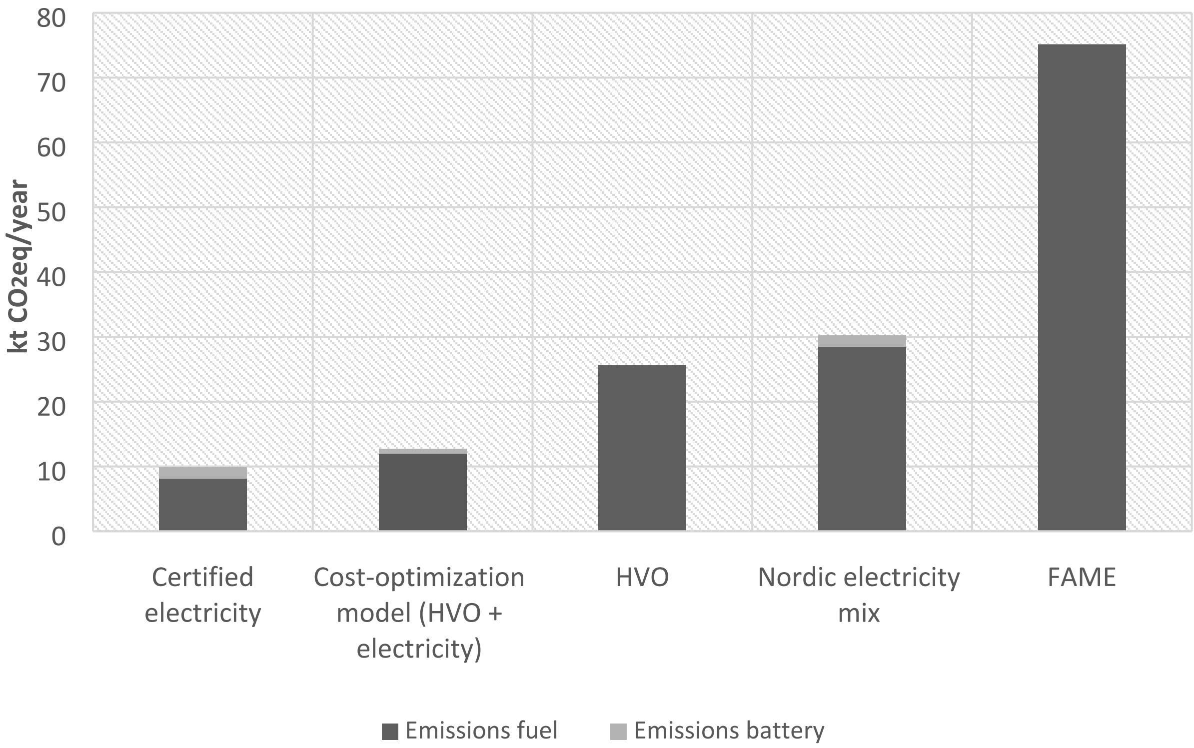



**Figure 6: Emissions (in kt $CO_{2eq}$/year) of the bus network when running on a single fuel in comparison with emissions estimated by the cost-optimization model (91 bus routes running on HVO and 52 bus routes running on certified electricity)**

## 4.2 Sensitivity analysis considering battery characteristics

A sensitivity analysis has been carried out for the battery-associated emissions, which were earlier presented in Table 3. This is done by changing the specific battery emission parameter. The sensitivity range is from -20% to 180% of the parameter's original value (6,190 $gCO_{2eq}$/kg battery , see Section 2). This range is in line with the specific battery emission values estimated in previous literature (see Section 3.1.2). Figure 7 shows the linear impact of battery emissions on the overall emissions of the selected bus network when this parameter changes. The change starts at 1% of the total emissions for the lower margin and reaches 9% of the total emissions for the higher margin. This confirms what was mentioned in Section 4.1, i.e. that the majority of emissions of the bus network originates from fuel-related emissions, and not from battery-related emissions.

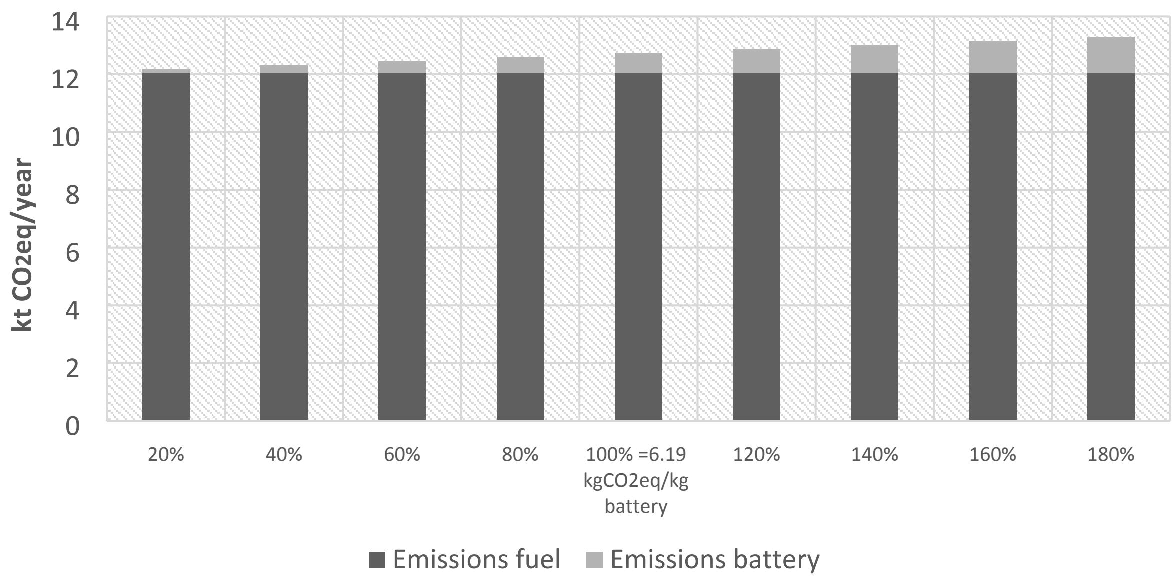



**Figure 7: Sensitivity analysis on the total emissions (in kt$CO_{2eq}$/year) estimated in the optimization model for varying specific battery emissions (in g$CO_2$eq/kg battery)**

There are 143 bus routes considered in the model, and it is assumed that 10 buses operate each route. From the investigated bus routes, 52 are electrified in the cost optimization model, thus 520 buses are electric. With the assumed battery capacity of 60 kWh, energy density of 80 Wh/kg, and one battery change per bus, the total battery weight that is taken into account in the sensitivity analysis is 390 tons.

The next sensitivity analysis applied to the model focuses on varying battery sizes, i.e., the battery capacity. A range between a minimum of 10kWh and a maximum of 300kWh is considered in order to illustrate the differences in the electrification potential of the bus routes, and the emissions associated to each system configuration. It should be noted that a battery with 300 kWh capacity only requires charging at the depot. In that case, opportunity charging is not needed along the route.

Figure 8 shows the result of the sensitivity analysis when varying the battery capacity. The share of battery emissions varies from 0.25% with a battery capacity of 10kWh to 30% with a battery capacity of 300 kWh. When the battery capacity increases, the emissions associated with the fuel consumption decrease, due to the electrification of a higher number of bus routes. This is due to the fact that with higher battery capacities longer routes could be electrified. On the other hand, the impact on emissions from the batteries also increases and, with a larger number of electric buses, more batteries are used. In addition, batteries with higher capacity are larger and heavier, which is also associated with higher life cycle carbon emissions.

Thus, from the emissions perspective, a larger battery (i.e. with capacity of 300 kWh) is not advantageous, regardless of the fact that higher electrification rates can be more easily achieved. The most positive results in terms of emissions reductions of the bus network selected are obtained with a battery capacity of 120 kWh. In this case, the increase of battery emissions is compensated by the decrease in emissions due to the use of renewable electricity.

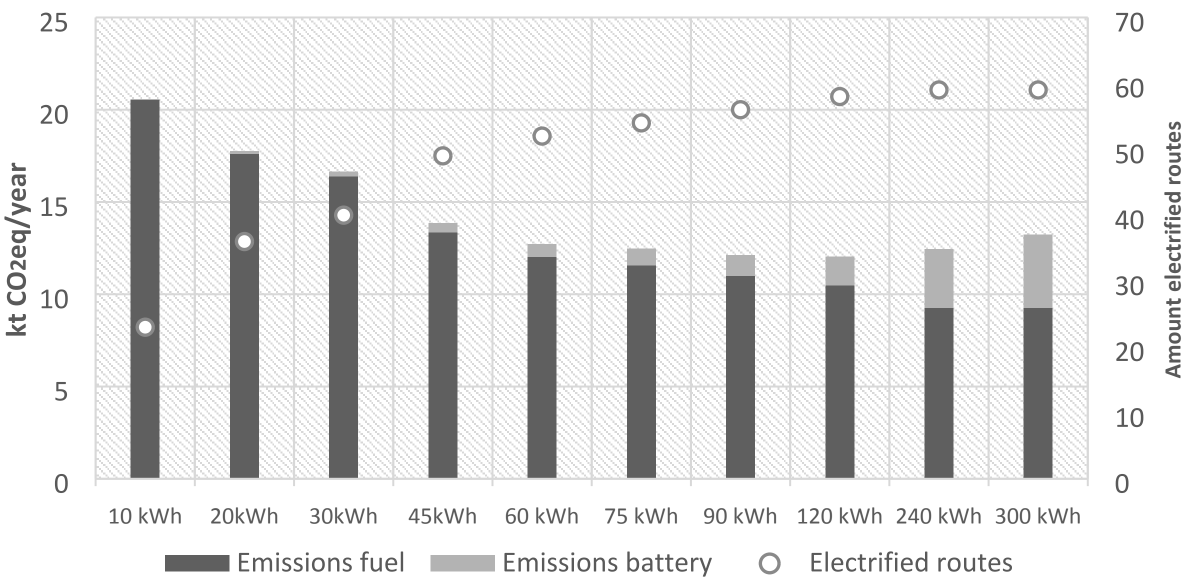



**Figure 8: Sensitivity analysis of total emissions in relation to battery capacity**

It should be pointed out that this estimation does not take into account the fact that the larger the battery is, the more it weighs. This added weight could affect the energy consumption of the bus negatively, as well as reduce passenger carrying capacities. Methodologies for evaluating the impact of such effects on greenhouse gas emissions of electric and electric hybrid vehicles have been developed in detail in Meinrenken and Lackner (2015).

In our case, we use a simpler approach that fits well with the structure of the optimization model to estimate the variations in energy consumption depending on the battery weight. The proposed value in Sinhuber et al. (2012) for estimation of traction energy consumption in relation to the battery of the bus is equal to *0.072 kWh/km * t*, where t is the total weight of the bus in tons. The curb weight of the bus is assumed to be 12.5 tons in the case of a 12-meter bus in line with Göhlich et al. (2014). From the above the traction-related energy consumption is calculated and the auxiliaries' energy consumption is then added in order to obtain the total energy consumption per kilometer. The difference in the consumption for a 10 and 300 kWh battery is 29%.

Figure 9 shows the effect of battery weight-related energy consumption on the results of the sensitivity analysis for varying capacities. The difference in fuel-associated emissions shown in Figure 8 and 9 are small for battery capacities below 60 kWh. This can be explained by the fact that smaller shares of the bus network are electrified, thus having lower impact on emission reduction compared to bus routes running on biodiesel. This is not the case for battery capacities higher than 60 kWh, when more bus routes become electric and the batteries become heavier. For a battery capacity of 300 kWh, there is a 15% difference in fuel-associated emissions due to the higher energy consumption resulting from the heavier batteries. The point where the emissions are lowest is still somewhere between 90 and 120 kWh though.

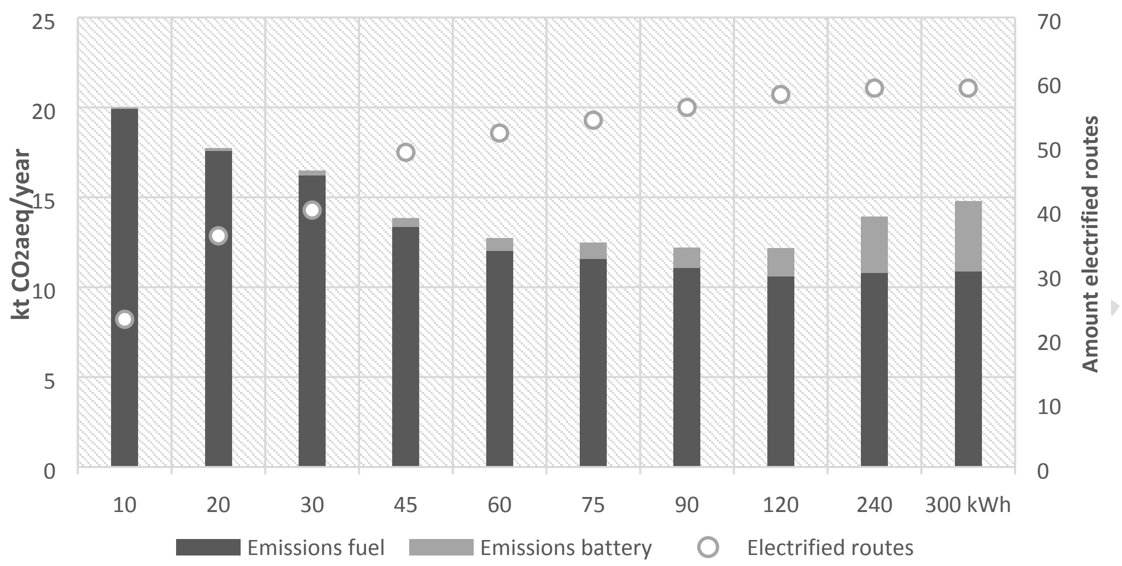



**Figure 9: Sensitivity analysis of total emissions in relation to battery capacity, adjusting the energy consumption to the weight of the battery**

Another aspect that should be discussed is that for the case of fast charging, power optimized batteries are used, while for the case of depot charging (slow charging) energy optimized batteries are preferred. The power optimized batteries have lower energy density but can withstand higher charging power, and they also have a longer life than energy optimized batteries. For example, in Lajunen et al. (2018) the power optimized batteries have double cycle life than energy optimized batteries. On the other hand, energy optimized batteries have higher energy density and therefore can store more energy per kg of their mass.

The effects on battery life from the various charging strategies (fast vs. slow charging) are not captured in detail in this model. Although power optimized batteries are costlier than energy optimized batteries (a difference of 40% in costs per kWh, see Lajunen et al. (2018)), still their smaller size (in terms of capacity in kWh) and longer cycle life compared to the energy optimized batteries could lead to a similar range of total battery costs, even if more replacements would be needed for batteries withstanding fast charging.

It should be noted that higher energy densities (both for power and energy optimized batteries) could help to 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. Figure 10 shows the results of the sensitivity analysis for different values of the battery's specific energy. It can be observed that the share of battery emissions decreases as the specific energy increases, while the share of emissions from fuels remains stable. This result is expected and shows that the better the energy density of the battery, the lower its impact will be on the emissions. On the other hand, a battery of higher energy density will cost more. The results are in line with findings of LCA studies in the literature, such as in Held and Schücking (2017), where a positive overall impact GWP from electric vehicles is estimated based on empirical data from battery electric vehicles. However, the potential negative effects of battery usage on some of the LCA impact categories, such as the acidification potential, are highlighted.

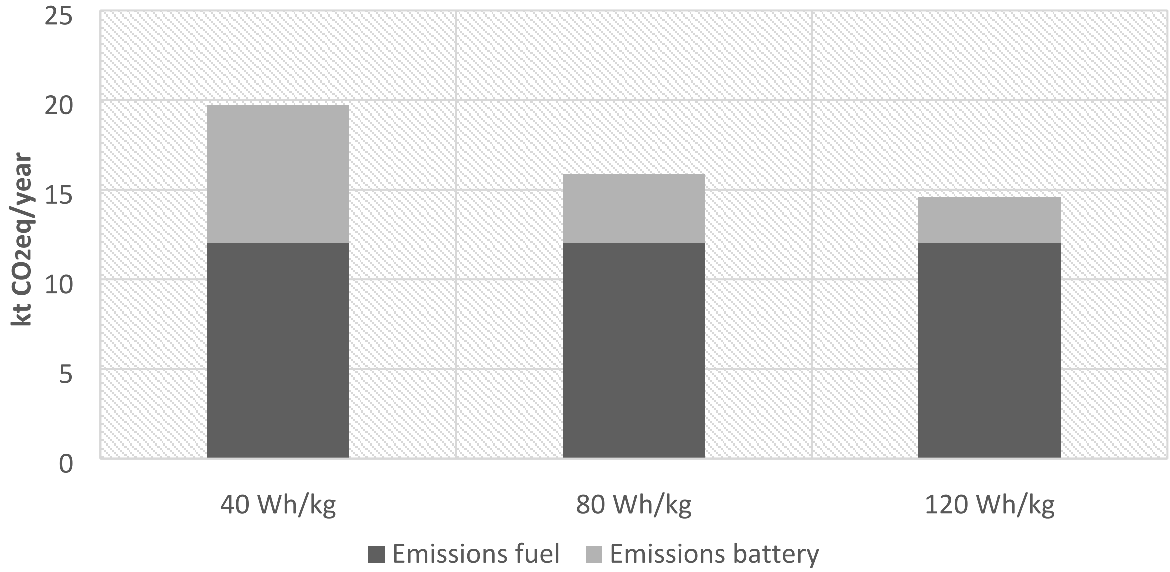



**Figure 10: Sensitivity analysis on total emissions in relation to the energy density of the battery**

## 4.3 Inner city electrification and air quality

There are differences between the local and global impacts of transport emissions. Fuel emissions refer to local emissions, while battery-associated emissions occur at the global level, during production stages. A detailed LCA can give the global environmental impact of each option, which has to be considered also in relation to the local impacts.

Road transport electrification could have significant impact on air quality improvement in dense urban environments. Electric vehicles have no exhaust gases and, therefore, could help to reduce local air pollution. This is a universal problem and, even if Stockholm enjoys good air quality in general, there are particular bottlenecks where congestion leads to air pollution, especially in the inner city. The limits for the harmful Nitrogen Oxide ($NO_x$) levels have been surpassed multiple times in the year 2016 in air quality measurement stations located in busy streets of Stockholm's inner city, such as Hornsgatan, Sveavägen, and Norrlandsgatan (Hurkmans et al., 2017). Similar observations can be made for $PM_{10}$ limits (SLB analys, 2016). Electric buses can be part of the solution against air pollution in Stockholm's inner city.

Most of the bus stops selected by the model for installing charging infrastructure are located in the inner city. This is not surprising as this is where the higher concentration of major public transport hubs are, and thus also the location of potential charging stations. From a total of 480 bus routes operating in the Stockholm region, 161 routes cross the inner city, and 21 routes are completely within the inner city limits. From these 21 routes, the model identifies 10 that could be electrified. The electrified routes and charging locations are shown in Figure 11. The analysis in this section refers to these routes.

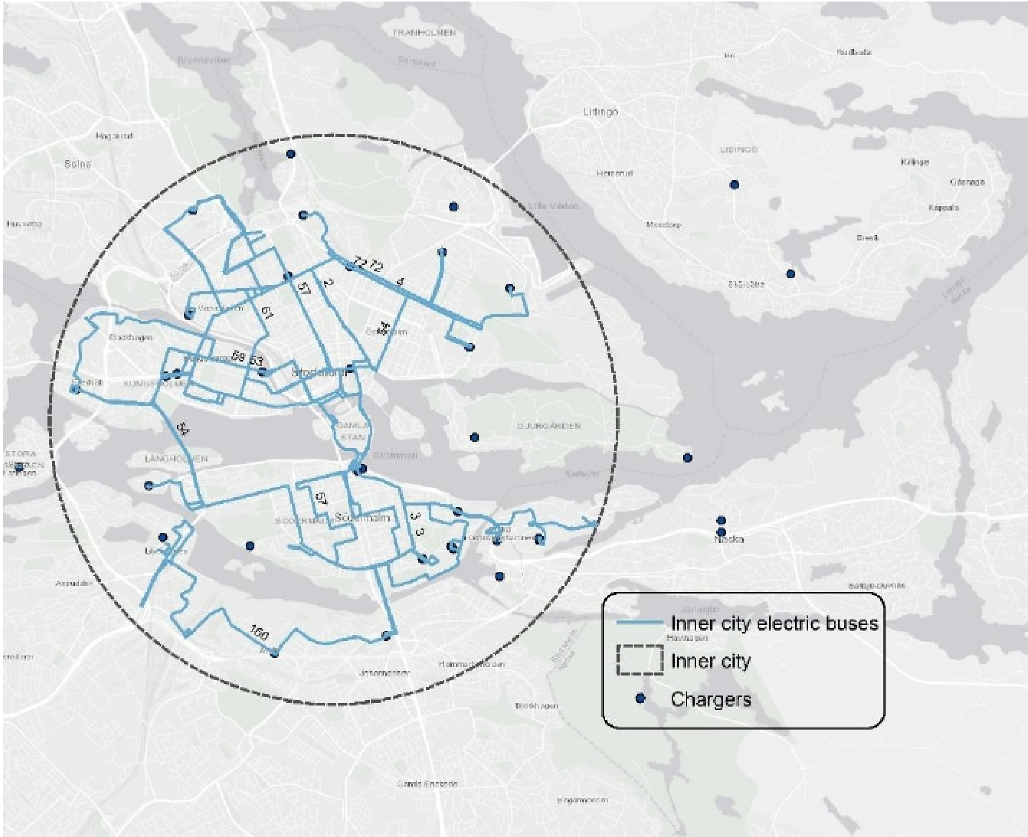



**Figure 11: Bus electrification in Stockholm's inner city – electrified bus routes and location of chargers**

From the schedule, the unique trips can be extracted. When multiplied with each route's length, the total daily bus transport volume (in vehicle kilometers) is obtained. The transport volume for the 10 inner city routes that are electrified is 44846 vehicle-km/day. If the electric bus energy consumption is assumed to be, on average, 1.5 kWh/vehicle-km and the biodiesel (HVO) bus consumption is 4.5 kWh/vehicle-km, the electrification of these routes leads to energy savings equivalent to approximately 44 GWh/year. These savings represent 6.4% of the current total energy consumption of Stockholm's bus fleet (690 GWh/year according to Svensk Kollektivtrafik, 2017). Statistics published on the Swedish Public Transport Association's database show the average levels of pollutants from Stockholm's buses in 2016 (see Table 2).

The above mentioned energy savings and transport volume lead to avoided exhaust emissions. Table 4 summarizes the amount of avoided pollutants, when taking into amount the total annual transport volume of the selected inner city routes. Previous reports show that the total amount of $NO_x$ from road transport for the whole of Stockholm city was 3100 $tNO_x$ /year, while $PM_{10}$ was 860 $tPM_{10}$/year (Länsstyrelsen i Stockholms Län, 2012). Assuming that this is the current range of annual $NO_x$ and $PM_{10}$ emissions from road transport in Stockholm, removing the emissions from buses would lead to approximately 2% reduction in $NO_x$ emissions and 0.05% reduction in $PM_{10}$ emissions from road transport in Stockholm, as listed in Table 4. The limited potential impact obtained for local pollution is not surprising as transport volume and pollution related to private and goods transport is much larger than for bus transport. On the other hand, when specific corridors in the inner city are assessed, these reductions can be significant, as the share of public transport volume there is larger.

**Table 4: Avoided NOx, PM and $CO_2$ emissions for proposed electrification of inner city routes (calculations based on Table 2 and estimated annual transport volume of inner city routes)**

| Pollutant | avoided pollution from inner city electrification (t/year) |
|---|---|

| | |
|---|---|
| $NO_x$ | 60 |
| $PM_{10}$ | 0.49 |
| $CO_{2eq}$ | 5160 |

It should be noted that tailpipe emissions can be greatly affected by local conditions, such as elevation, road traffic, and the specific fuel blends used. The values reported for Stockholm are much lower than other studies observed in literature, such as Cooper et al. (2014) were $NO_x$ and $PM_{10}$ estimations for buses using NExBTL fuel (a market name for HVO from the company Nesté) show approximately doubled values compared to Stockholm. More specifically, the $NO_x$ emissions were around 7 g/km and the PM were around 0.08 g/km in this meta-analysis (Cooper et al., 2014). In Stockholm, there is a significant amount (approximately 30% of the fleet) of non-diesel engine buses that have lower $NO_x$ and $PM_{10}$ emissions than their diesel counterparts. More specifically, in 2016, out of the 2149 buses comprising the public transport fleet, 324 were gas engine buses and 369 were ethanol buses (Svensk Kollektivtrafik, 2017b).

## 5. Conclusions

This paper evaluates the impact of large-scale electrification on life cycle emissions of the Stockholm bus network. An optimization model is applied for the bus network of the city of Stockholm. In an earlier study by Xylia et al. (2017a), the model focused on total operation cost and energy consumption. Here, the focus is on emissions from the various fuels used, as well as the batteries needed for the electric buses. These two aspects are assumed to have the largest impact among other system components and are thus investigated in detail. The battery emissions, battery capacity, and specific energy were subjected to sensitivity analysis.

Higher battery capacities could support the electrification of larger parts of the bus network and therefore reduce emissions associated with fuel consumption. However, the analysis indicates that this does not necessarily lead to lower emissions in total. This is due to the fact that batteries of higher capacity are larger and heavier, and lead to higher carbon emissions. Moreover, the results of this analysis show 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 show that a battery capacity of 120 kWh has a better life cycle impact than, for example, a 60 or 300 kWh battery.

Moreover, the life cycle emission impact from batteries decreases at higher energy density values. This indicates that batteries with denser specific energy are preferable from an emissions point of view. It is expected that technology improvements in batteries shall lead to reduced environmental impact, as well as an improved ratio for the battery weight and its capacity. This would result in less overall energy consumption and emissions from electric buses.

The results highlight the impact of fuel choices on the environmental impact of a bus network operation. The use of renewable electricity of lower life cycle emissions is a better choice than first generation biofuels, for example. The use of first generation biofuels should additionally be discussed in the context of the “food vs. fuel” debate (see, for example, Silveira and Johnson (2016)). However, the use of second generation biofuels, such as HVO, can directly compete with electricity mixes of low environmental impact, such as the Nordic electricity mix. Therefore, it is necessary to choose electricity from renewable sources in order to obtain the full benefits from electrification. The certified renewable electricity for the Swedish case has an emission factor which is 90% lower than the emission factor of the average Nordic electricity mix.

According to the model results, a 100% electrified bus network would not be the cost-optimal solution. The implementation of such a solution would require high investment costs on infrastructure which could not be balanced by the reduced fuel costs. We propose a solution where electricity and biodiesel routes co-exist, with higher rates of electrification in the city centre, where most of the benefits of improved local air quality due to electric buses could be accrued. The results show that the impact on emissions from this combined solution is actually quite close to the impact of a fully electrified bus network, and this is also due to the fact that battery-related emissions are lower under this configuration.

Electrification can help to reduce local air pollution caused by buses in the inner city, such as $NO_x$ and PM. However, the analysis indicates that the overall impact of such reduction would be small compared to the local pollution caused by private transport. Thus, electrification of bus fleets should be implemented in combination with strategies for increased use of public transport, in order to maximize road transport emission reduction in urban environments.

Future research should focus on lifecycle impacts of batteries and charging stations (for both fast and slow charging) required for electrification which could be subject to sensitivity analysis under various lifecycle lengths. Additionally, exploring the differences in terms of lifecycle impacts from various battery types and chemistries would be beneficial in understanding the implications of battery-related choices for electrification of road transport.

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## Abbreviations

| | |
|---|---|
| EU | European Union |
| FAME | Fatty Acid Methyl Ester |
| GA | Genetic Algorithm |
| GAMS | General Algebraic Modeling System |
| HVO | Hydrotreated Vegetable Oil |
| LCA | Life Cycle Analysis |
| NOx | Nitrogen Oxide |
| PM | Particle Matter |
| SEK | Swedish Crown |
| VOC | Volatile Organic Compounds |
| WTW | Well-to-Wheel |

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## Appendix

**TableA.1. Parameter values used in the model**

| Parameter | Value | Source |
|---|---|---|
| **Energy consumption bus (kWh/km)** | | |
| Biodiesel bus | 4.50 | adjusted from Mahmoud et al., 2016 |
| Biogas bus | 6 | adjusted from Hagberg et al., 2016 |
| Electric bus | 1.50 | adjusted from Hagberg et al., 2016; Lindgren, 2015; |
| **Maximum battery capacity (kWh)** | | |
| Electric bus | 60 | Lajunen and Lipman, 2016 |
| **Minimum state-of-charge (SOC) for the battery (%)** | | |
| Electric bus (opportunity charging) | 30 | Kunith et al., 2016 |
| **Power capacity charging station (kW)** | | |
| Electric-Conductive | 300 | Bombardier, 2016; Siemens, 2016 |
| Electric-Inductive | 200 | |
| **Infrastructure costs (SEK[1])** | | |
| ***Charging station costs (SEK)*** | | |
| Electric-Conductive | 1,500,000 | Lindgren, 2015 |
| Electric-Inductive | 2,000,000 | |
| ***Pickup for charging station (SEK)*** | | |
| Electric-Conductive | 0 | Lindgren, 2015 |
| Electric-Inductive | 1,000,000 | |
| ***Battery (SEK/Wh)*** | | |
| Electric-Conductive | 10 | Lindgren, 2015 |
| ***Fixed installation costs (SEK)*** | | |
| Grid connection | 175,000 | Lindgren, 2015 |
| Grid connection annual fee | 40,000 | |
| Building costs and permits | 400,000 | authors' assumption |
| **Vehicle costs (SEK)** | | |
| Biodiesel bus | 2,500,000 | Lajunen and Lipman, 2016 |

| | | |
|---|---|---|
| Biogas bus | 3,000,000 | SLL, 2015 |
| Electric bus | 4,500,000 | |
| **Operation & Maintenance (O&M) costs (SEK/km)** | | |
| ***Driver cost*** | | |
| Salary costs, insurance etc. | 16.40 | Hagberg et al., 2016 |
| ***Maintenance*** | | |
| Biodiesel bus | 1.50 | Lajunen and Lipman, 2016 |
| Biogas bus | 3 | Hagberg et al., 2016; SLL, 2015 |
| Electric bus | 3 | |
| **Fuel costs (SEK/km)** | | |
| Biodiesel bus | 6.40 | SLL, 2015 |
| Biogas bus | 7.10 | |
| Electric bus | 1.40 | |

*[1] SEK is the Swedish currency (Swedish Krona). The average exchange rate for 2016 is 1SEK = 0.095€ (Oanda, 2018)*

**Table A.2. Indices, variables, and parameters used in the optimization model**

| | |
|---|---|
| **Indices** | |
| l | bus route |
| s | bus stop |
| tech | bus technology (biodiesel, biogas, or electricity) |
| **Binary Variables** | |
| $US_{l,s,tech}$ | binary variable indicating if charging station is installed at bus stop {0,1} |
| $TUS_{l,tech}$ | binary variable associating bus routes with specific technology {0,1} |
| **Positive Variables** | |
| $C^{total}$ | total costs |
| $E^{total}$ | total energy consumption |
| $U^{total}$ | total emissions |
| **Parameters** | |
| $C^{O\&M}_{l,tech}$ | operation & maintenance costs of the technology (tech) that belongs to bus line (l) |
| $C^{fuel}_{l,tech}$ | annual fuel costs of the technology (tech) that belongs to bus line (l) |
| $C^{infrastructure}_{l,tech}$ | annualized costs for infrastructure of the technology (tech) that belongs to bus line (l) |
| $C^{vehicle}_{l,tech}$ | annualized costs for vehicles of the technology (tech) that belongs to bus line (l) |

| | |
|---|---|
| $Cap_{tech}$ | maximum power stored in the bus using the technology (tech) |
| $Cons_{tech}$ | power consumption per bus using the technology (tech) |
| $EB_{tech}$ | emission factor for battery based on technology (tech) |
| $EF_{tech}$ | emission factor per fuel for each technology (tech) |
| L | number of bus routes |
| $\tilde{L}$ | set of all bus routes |
| $Life^{battery}$ | battery lifetime |
| $L_l$ | length of the bus route |
| $N_l^{vehicle}$ | number of vehicles deployed for operating each route (l) |
| $N^{battery\ change}$ | number of battery replacements assumed for bus lifetime |
| $SEB_{tech}$ | Specific energy of the battery |
| $TC_l$ | total annual number of trips for the bus route (l) |
| TECH | number of technologies |