CHALMERS
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Impact of electrified bus transport on the electricity system of Gothenburg

Can electric buses provide a service to the electricity system?

Master's thesis in Sustainable Energy Systems

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Department of Space, Earth and Environment
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2020

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Abstract

The electrification of public bus transport is regarded as an important step in decarbonising metropolitan areas, yet little is known about its effects on the energy system of cities. Assessments in previous research do not explicitly account for the interconnection between electrified public bus transport and the energy system. This thesis studies how battery electric buses (BEBs) and the city energy system affect each other. To study electric buses in this context their driving and corresponding charging demand must be understood. This thesis aims to understand the impact of electrified bus transport on the energy system of Gothenburg, Sweden. A three-part method is employed. First, a model creates a network of electrified inner-city buses in Gothenburg and determines their time-resolved electricity demand for charging. Second, the charging of buses is matched to an electricity cost profile, and charging is delayed such as to minimise electricity costs for charging while fulfilling all transport demand in the network. Third, the electricity demand of the BEBs is added to a cost-minimising linear optimisation model of a city energy system. It models dispatch and investments in the energy system in a scenario with net zero CO_2 emissions from heat and electricity generation in the city, and limitations in electricity import capacity. In the energy system model, the charging of the buses is delayed such as to reduce the total city energy system cost. The findings suggest that, although peaks in electricity demand of buses and the city overlap in time, BEBs have negligible impact on composition and operation of the energy system. However, benefits can be derived from delaying charging of buses to low electricity cost events, reducing the buses' charging cost and the afternoon peak in the BEBs' electricity demand. The findings also show a synergy between the fast charging bus network and the generation from photovoltaic solar power, where a part of the demand from the charging of buses during the day can be satisfied by generation within the city.

Keywords: electric buses, electrification, smart cities, Gothenburg, public transport, charging optimisation, renewable energy, electricity demand

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Rasmus Erlandsson and Henrik Hodel, Gothenburg, June 2020

Glossary of terms

EU - European Union
CO_2 - Carbon dioxide
Solar PV - Solar photovoltaics
EAEB - Energiförsörjningsalternativ för elektrifierade bussystem (engl: Energy supply alternatives for electrified bus systems). A computer program for creating electrified bus networks
SoC - State of Charge, the energy level in batteries.
HPC - High-powered charger (in this study, chargers above 100kW)
BEB - Battery electric bus
PTO - Public transport operator, a company that owns and/or runs the buses.
Opportunity charging - Charging at multiple opportunities during the period of operation. In the case of buses this is typically done at the turn-around stop with high-powered chargers that connect via pantographs.
Depot charging - Charging outside of regular operation at the bus depot, typically with low charging speeds and long charging duration.
Trunk routes - High-capacity bus routes in Gothenburg, Sweden that typically use articulated buses. Operation spans from early morning to nighttime with a high frequency of trips.
City routes - Lower-capacity bus routes in Gothenburg, Sweden that also operate within the city suburbs. The hours of operation are often limited to daytime and the frequency of trips lower than on trunk routes.
UWET - Unwanted Wireless Energy Transfer, a phenomenon arising when buses are modelled using aggregated batteries. It allows buses that are not in operation to charge those that are in operation without having to stop for charging.
Peak bus - A bus that operates during the periods of peak demand or rush hours.
Middle bus - A bus that does not operate during nighttime
Base bus - A bus that operates during all hours of the day, except for a few hours of the night.
BSRR - Bus system reserve requirement, a requirement on reserve generation of the electricity system that is determined by the difference between current and maximum power usage of the buses charging infrastructure
CBSRR - City bus system reserve requirement, similar to BSRR but only for city buses. It is represented by a constant value of 11.25 MW.
Availability - A parameter which indicates whether a bus is currently in driving operation or not. It is used to determine how much of the aggregated fleet is available for charging at the depot.
PtH - Power to Heat, technologies like heat pumps and electric boilers that convert electricity to heat.
CHP - Combined Heat and Power, a power plant that through incineration creates both useful electricity and heat.
CCGT - Combined Cycle Gas Turbine, A power plant gas turbine that has been coupled with a steam cycle to further increase its electricity efficiency.

Fixed load - an electric load that is not able to be delayed for smart charging
Flexible load - an electric load that can be delayed for smart charging
PP - Percentage Points

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1
Introduction

1.1 Background

The EU has mandated a reduction of greenhouse gas emissions from transportation by 60% until 2050, compared to 1990 [1]. The city of Gothenburg has ratified EU goals and set targets of its own. A reduction of CO_2-emissions from road traffic by 80% until 2030 (compared to 2010) is pursued [2]. Accomplishing these goals necessitates a change in energy carriers away from fossil fuels. Additionally, Gothenburg's targets regarding air quality and noise in the city cannot be met by buses with internal combustion engines [3]. For buses, electrification has therefore presented itself as a compelling alternative.

The feasibility of electrification of the bus system in Gothenburg has been assessed by several local actors in a joint report [4]. Aspects such as electricity generation and transmission capacity as well as project costs and policies have been evaluated. The consensus was that electrification of the bus system in Gothenburg is possible to implement, however some challenges were identified when considering other developments in the city. For instance, the advent of electric charging for personal vehicles can generate unpredictable electrical loads. Consequently, limitations regarding electricity transmission capacity in the city can arise.

To reduce the congestion in the grid, local and regional transmission networks can be fortified, but this is a long process and therefore not guaranteed to be finished in time [3]. Furthermore, several cities are already experiencing bottlenecks in transmission today, especially since adding transmission capacity is difficult in the short term [5]. This makes reinforcement of transmission capacity an unlikely sole solution to overcome the problem, and other measures are needed, especially in the short term. It has been suggested to better utilise the current system by exploiting flexibility in loads and generation [4, 5].

Improved utilisation of the electricity system is an aspect of so called *smart cities*. Previous work on the electricity system of smart cities covers improved integration of energy technologies, such as heating systems, heat storage, solar PV and stationary batteries [6]. This thesis aims to first and foremost establish electric load profiles for an electric bus public transport system. These enable integration of the load from electric buses in the city energy system modelling. With the coupling in the model, it can be revealed how charging of electric buses impacts hourly dispatch, and investment of energy technologies. A major question is whether smart charging strategies could reduce peak generation in the electricity system compared to charging strategies that do not consider effects on the energy system. This has previously not been assessed by means of time resolved electricity demand profiles of electric buses integrated into a city energy system optimisation model.

1.2 Aim

This work aims to understand the impact of electrified bus transport on the energy system of Gothenburg, Sweden. The impact on the electricity system is studied by using the load profiles from the electric buses as inputs in a city energy system optimisation model. In the city energy system optimisation, the effects and limitations of smart charging electric buses are studied.

More specifically, this thesis work aims to answer the following questions:

1. How does the electricity demand from the electrified bus system vary with respect to power and time?
2. Which factors limit the potential for smart charging of electric buses to benefit the city electricity system?
3. To what extent can smart charging of buses affect the city energy system with regards to system cost, composition and dispatch?

2
Methods

The methodology of this thesis consists of three main parts: **(i)** applying bus route timetables to create a representation of the electrification of the entire trunk and city bus system of Gothenburg and determining its electricity demand on a minute and hour basis, **(ii)** optimising the charging of the created bus system with regard to *electricity cost of charging buses* by controlling charging events on a minute- and bus scale, **(iii)** optimising the charging of the created bus system with regard to *total energy system cost* by implementing an aggregated version in a cost-minimising city energy system model.

A complete flowchart of the method, with in- and outputs for each step, is shown in Figure 2.1. Part **(i)** utilises a tool called *Energiförsörjningsalternativ för elektrifierade bussystem* (Energy supply alternatives for electrified bus systems), EAEB [7], to determine profiles for charging and the battery state of charge (SoC) of buses. These data, together with hourly electricity cost data are used in part **(ii)** to obtain optimised charging patterns for each bus in the system. Part **(iii a)** covers the processing of data from **(i)** by aggregating and categorising the buses, which is used in **(iii b)** to integrate the bus network in the city energy optimisation model.

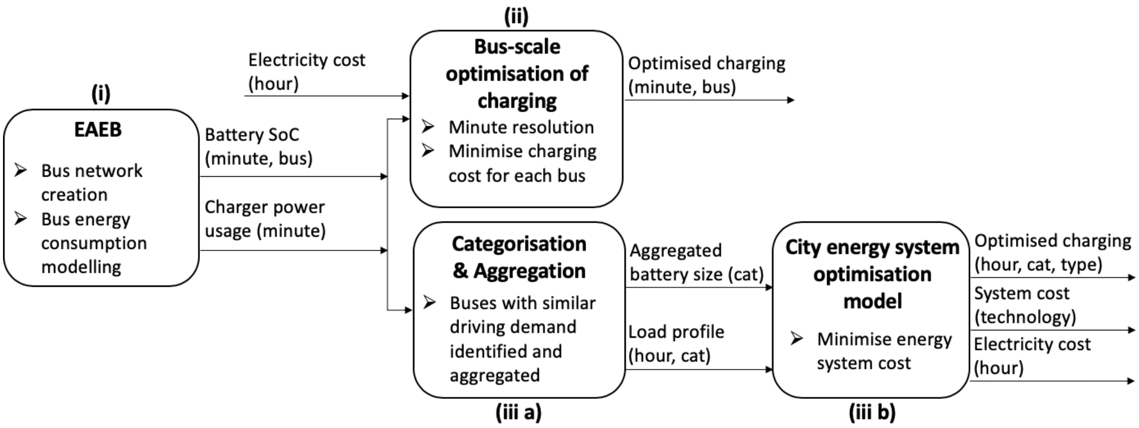

Figure 2.1: Coupling of parts in the method.

Several cases are modelled for both **(ii)** and **(iii)** to investigate the effect of smart and direct charging strategies. In the context of this thesis, smart charging refers to the possibility of altering the timing and duration of charging in a manner that reduces the direct costs for charging or the total cost of the electricity system. Direct charging corresponds to charging according to a predetermined pattern in which the buses charge at turnaround stops after each trip. Two cases of a bus scale model optimisation and three cases for a city scale optimisation are presented in Table 2.1 and further explained in their respective sections in the method.

Table 2.1: Modelling cases covered in this work. The roman numerals correspond to the cases' part of the method.

Modelling case	Bus scale (ii)		City scale (iii)		
	Bus Direct	Bus Smart	City Only	City Direct	City Smart
Model context	Price curve from model "City only"		Gothenburg 2050, low-cost PV, net zero CO_2-emissions from heat and electricity generation		
Buses included	Trunk only	Trunk only	No	City & Trunk	City & Trunk
Energy system modelling	-	-	Yes	Yes	Yes
Optimisation objective	-	Minimise charging cost	Minimise total energy system cost		
Aggregation	Aggregated	No aggregation	-	Aggregated	According to category
Categorisation	-	-	-	-	Trunk only
Time resolution	Minute		Hour		

2.1 Creation of Gothenburg's bus system

This section describes how the EAEB tool is used to assign trips to buses according to the timetable. The utilised charging solution is presented, followed by an explanation of how the energy consumption is determined.

The primary use of the EAEB tool in this work lies in formulating the driving demand and translating it to electricity demand. Driving demand and bus routes with stops are known through a timetable database for Gothenburg featured in EAEB. The tool allows for the creation and management of a bus network consisting of multiple routes integrated with scheduling of individual buses. Charging infrastructure and charger placement can be altered in conjunction with bus-related parameters to illustrate different cases. Charging infrastructure refers to the selection of fast charging opportunity chargers or depot charging. Figure 2.2 showcases the inputs to, functionalities within, and outputs of the EAEB tool.The technical parameters are illustrated in Table 2.2 along with the selected bus routes in Table B.1.

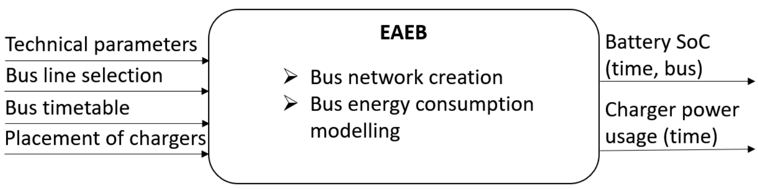

Figure 2.2: Overview of method for **(i)**.

2.1.1 Bus network creation

The majority of public transportation by bus in the city of Gothenburg is satisfied by two classes of bus routes: trunk bus routes and city bus routes. Trunk bus routes typically feature larger buses (18 m) that satisfy a high driving demand. The variation in driving demand is greater for city buses than for trunk buses and city buses often change between bus routes during the day. According to Västrafik's [1] timetable [8] there are eight trunk bus routes. 38 additional routes operating in the city are included in this thesis, termed city bus routes.

Other classes of bus routes operate in the city, yet they are not considered in this work, as a significant share of their routes lie outside of the city borders. An overview of the exact bus routes included in this work can be found in Table B.1 of Appendix B.

An analysis of the bus timetable reveals that the driving demand of weekdays is identical, whereas Saturdays and Sundays each have their own driving demand. For use in part **(iii b)**, the findings of part **(i)** will have to span an entire year. To forego the need of modelling all days of a year individually, a representative week is created and extrapolated to a year. Tuesday 20 September 2016 was selected as a representative weekday and Saturday 24 September 2016 and Sunday 25 September 2016 comprise the weekend. These days were selected since they are part of the available period of the timetable in the EAEB tool and are representative for the regular traffic operation[2].

The bus charging infrastructure in this work consists of high-power chargers (HPCs) with 450 kW charging power capacity at the turnaround stops of each route. A system of HPCs is shown to be a cost-effective method for electrification [9] and the charging infrastructure used for the already electrified bus routes in Gothenburg [10]. Depot chargers are also installed at the depot. The chargers are rated at 50 kW each, and every bus has access to its own charger in the depot. In EAEB no depot charging is utilised since the charging demand is met by the HPCs. However, the depot chargers will be used in coming methods.

Figure 2.3 illustrates how trips of the timetable are assigned to buses. The EAEB tool assigns a sequence of trips with corresponding return-trips to each bus of the network. Buses are added until all trips of the route have been assigned. Charging occurs between trips at the HPCs. The network is created route by route for the representative week in this manner. An illustration of the complete network for route 16 can be found in Figure B.1 of Appendix B.

[1]Västtrafik is the agency responsible for public transport in Gothenburg, owned by the regional council of Västra Götaland, Sweden.

[2]The timetables in Gothenburg consist of a summer period of 1-2 months with reduced traffic, and a period of regular traffic during the remaining year

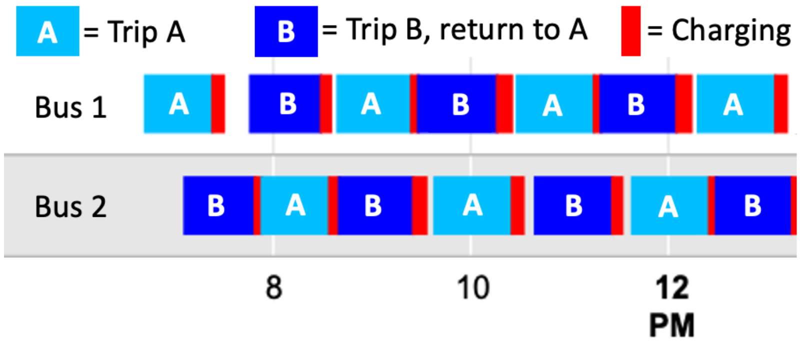

Figure 2.3: This excerpt of the bus network illustrates how trips of the timetable are assigned to buses and the timing of charging events.

Due to limitations in the EAEB tool it is not possible to simultaneously integrate all routes in a single network. Instead, a network is created for each route individually. Consequently, the buses cannot be used to their theoretical maximum capacity as trips from one route cannot be assigned to available buses from another route. Therefore, more buses are added to the entire network in total than strictly necessary. This effect is more prominent for the city buses which, in reality, can change routes multiple times during the day. Due to this issue, city buses are treated differently than trunk buses in some parts of the methods. Whenever this is the case, it is mentioned in the affected parts in the following sections.

2.1.2 Bus energy consumption modelling

Electricity demand in EAEB is expressed as battery charging load divided by the charging efficiency. In this model, the charging efficiency is set to 90 % throughout the model. The charging load is determined by the electricity consumption of the electric buses, which in turn is determined by the vehicle parameters of the model. Vehicle parameters are integrated in a battery energy balance, which keeps track of battery state of charge. The model assumes constant energy consumption per distance and adds net-consumption caused by elevation changes, as well as power consumption of auxiliaries such as electrical space heating and power steering.

Equation 2.1 specifies how the energy balance for each bus is conducted in the tool.

$$\Delta E_{\text{battery}} = C_s\,\Delta s + P_{\text{aux,el}}\,\Delta t + \frac{m_{\text{bus}}\,g\,\Delta h_{\text{gain}}}{\eta_{\text{powertrain}}} + m_{\text{bus}}\,g\,\Delta h_{\text{loss}}\,\eta_{\text{powertrain}} \tag{2.1}$$

where

Symbol	Value	Variable
C_s	varies by bus type	baseline specific consumption
Δs	varies by bus route	travelled distance
$P_{\text{aux,el}}$	varies by bus type	power requirement of auxiliaries e.g. el. space heating
Δt	varies by bus route	elapsed travel time
m_{bus}	varies by bus type	total bus mass
g	$9.81\,\text{m}\,\text{s}^{-2}$	gravitational acceleration of earth
h_{gain}	varies by bus route	elevation gain over the travelled distance Δs
h_{loss}	varies by bus route	elevation loss (negative sign) over the travelled distance Δs
$\eta_{\text{powertrain}}$	72 %	conversion efficiency from electricity to propulsion in the powertrain

Trunk buses are primarily modelled using a 18 m bus with a 300 kWh (gross) battery size, whereas the bus type of choice for city buses is a 12 m bus with a 200 kWh (gross) battery size. However, both city buses and trunk buses do contain both 18 m and 12 m bus types. The size of the electric bus for each route is selected to match that of the conventional buses used today. As an example, the bus type used for each trunk bus route is presented in Table 2.2. The denomination of the parameters is illustrated in Equation 2.1. The 12 m buses have a lower auxiliary power demand, battery size and baseline consumption than their larger counterparts. For route 50 & 60, the charge rate is limited by the buses rather than the charger. This is due to the smaller battery capacity of 12 m buses, which therefore cannot accept the high-power of 450 kW which the chargers can supply. The majority of city buses are 12 m buses and the same limitation applies to them. Note that in Table 2.2, the battery size is represented in terms of gross capacity. The available energy in the buses is set to 80 % of gross capacity.

Table 2.2: Bus parameters for trunk bus routes.

Route	Length [m]	Weight [kg]	$P_{\text{aux,el}}$ [kW]	C_s [kWh km^{-1}]	Gross battery size [kWh]	Max charge rate [kW]
16	18	28 000	15	1.85	300	560
17	18	28 000	15	1.85	300	560
18	18	28 000	15	1.85	300	560
19	18	28 000	15	1.85	300	560
25	18	28 000	15	1.85	300	560
52	18	28 000	15	1.85	300	560
50	12	19 000	10	1.25	200	375
60	12	19 000	10	1.25	200	375

The electricity consumption from buses travelling to and from the depot, at which the they could start and end daily operation, was not possible to include in the EAEB model. To account for the energy consumption caused by trips to and from the depot, a depot trip consumption addition is determined. The addition consists of the average driving demand for each trunk route that arises from either turn-around stop to the depot. The depot is assumed to be located at Järnbrotts Prästväg 31, 421 47 Västra Frölunda, where a new depot is currently being planned for the city's buses [11]. The depot trip consumption addition is added to the consumption profile every time a bus travels to or from the depot. Since the depot addition is done in post processing with a time resolution of one hour, the minute load profile for trunk buses does not contain the addition. This results in the addition only being used in method (iii). This procedure has not been followed for city buses, which entails that these are lacking the additional electricity consumption from travelling to and from the depot. Due to the number of city buses being overestimated during the network creation, the depot consumption would also be overestimated. The frequency of the depot addition is also difficult to determine for city buses, as buses could appear to be travelling to the depot but in reality be changing route instead.

2.2 Bus scale optimisation of charging

The model presented in this section aims to minimise the total cost of electricity for the charging of buses. The total cost of electricity is described by the objective function presented in Equation 2.2.

$$\mathrm{CC} = \sum_{bus}^{buses} \sum_{t}^{T} C_{(t,bus)}\, \mathrm{EC}_t \tag{2.2}$$

where $C_{(t,bus)}$ is the charging of each bus at each minute t, and CC is the electricity cost of charging the buses. EC_t is the marginal electricity cost at each minute t, originating from the *City only* modelling case in Table 2.1. The marginal electricity cost from the city model is created on an hourly basis, and the costs are assumed to be the same within the respective hour. The marginal cost of electricity generation acts as a proxy for the electricity cost, which typically includes additional overhead costs such as taxes and transmission fees etc. The marginal cost is the cost of the most expensive electricity generating unit, at hours with high solar PV generation, it is often the lowest. If the import capacity of the city is not fully utilised, the marginal cost is equal to or less than the cost of the national grid.

The model considers the hourly electricity cost, the battery SoC and driving demand data for each minute and individual bus, as well as limitations in charging capacity and battery storage level. Within this framework charging events for each bus are optimised for each minute of the day with the aim of minimising electricity cost. This model serves to illustrate the possibility of altering charging events on the scale of individual buses. The model is only used for trunk buses. City buses are not considered due to the number of buses within the created city bus network being overestimated, which in turn would overestimate their flexibility potential.

The periods studied in the bus scale optimisation each cover three days: Tuesday, Wednesday, and Thursday. These three-day periods are used in a summer period, 3-5/7, and a winter period, 9-11/1. The summer and winter periods are selected to highlight the impact the season has on the charging pattern and charging costs. In an attempt to obtain a representative charging cost, 52 three-weekday periods were modelled together with the electricity cost curve of the entire year. This period is created by linking the three-weekday period of each calendar week together. The electricity cost is approximated by the marginal electricity cost in the city, which represents a year 2050 scenario in which energy generation has zero net CO_2-emissions and an (50%) increase in electricity demand is assumed as compared to today's levels while the import capacity of electricity to the city is not extended. The electricity system context is described in further detail in section 2.3.

The buses are modelled according to a battery balance equation illustrated in Equation 2.3. The battery balance equation calculates the battery state of charge, $SoC_{t,bus}$ for each bus at each time t.

$$SoC_{(t,bus)} = SoC_{(t-1,bus)} + C_{(t,bus)}\,\mathrm{A}_{(t,bus)} - \mathrm{D}_{(t,bus)} \tag{2.3}$$

Bus driving demand, $\mathrm{D}_{(t,bus)}$, serves as an input parameter and determines how much energy is discharged from the battery of each bus per minute. An availability parameter, $\mathrm{A}_{(t,bus)}$, is derived from the driving demand, allowing charging only when there is no driving demand. If the bus is available for charging, then $\mathrm{A}_{(t,bus)}$ is equal to one. If the bus is not available (i.e. driving), $\mathrm{A}_{(t,bus)}$ is equal to zero. Charging, $C_{(t,bus)}$, is a variable determined by the model to minimise the charging cost, given the constraints placed on it.

A constraint is placed on the range of possible levels of SoC, see Equation 2.4. The min and max limits are supposed to reflect battery wear concerns and range anxiety of public transport operators (PTOs)[3].

$$b \leq SoC_{(t,bus)} \leq a \tag{2.4}$$

where a and b are the highest and lowest allowed battery storage levels, respectively. Similarly, charging $C_{(t,bus)}$ in the model is constrained to reflect charging power of opportunity chargers according to Equation 2.5.

$$C_{(t,bus)} \leq c \tag{2.5}$$

where c is the charging power of one opportunity charger[4]. The number of buses in the system is larger than the number of HPCs, which is why a constraint is placed on the combined charging power in the model. The constraint prevents the model from providing charging power greater than the combined power of installed chargers in the bus network. This is illustrated in Equation 2.6.

$$\sum_{bus}^{buses} C_{(t,bus)} \leq d \tag{2.6}$$

where d is the combined power of installed chargers. The constraints placed on the model are summarised in Table 2.3.

[3] A PTO is a company or a worker within the company that has as objective to create a bus network that satisfies the transport demand. The PTO has as objective to minimise the total cost of the bus network including bus cost, driver cost, insurance, fuel etc.

[4] One opportunity is rated at 450kW. Since the model is created with a time resolution of one minute it is converted to $kWh\ min^{-1}$. 450kW rated power during 1 min = 7.5 $kWh\ min^{-1}$

Table 2.3: Paramters for the constraints in Equations 2.4 through 2.6.

Symbol	Value	Constraint description
a	80 % of gross battery storage capacity	upper limit of possible battery SoC
b	20 % of gross battery storage capacity	lower limit of possible battery SoC
c	7.5 kWh min^{-1}	rated charging power of HPCs
d	$c \times$ number of chargers	rated combined charging power of HPCs

2.3 City energy system optimisation model

This section covers parts **(iii a)** and **(iii b)** of the method, shown in Figure 2.1. To begin, the city energy system model developed by Heinisch et al. [6] is introduced. Then, the categorisation and aggregation of buses are explained. This is followed by a description of the bus battery module in the city energy optimisation model, and reserve generation capacity.

The model presented in this section integrates the created electrified bus network into the future energy system of Gothenburg. Both investment and dispatch of electricity- and heat generating (and storage) technologies within the city boundaries are modelled with the aim of minimising investment and operational costs of the system.

The existing capacity of energy technologies is considered. Constraints are placed on the import of electricity to the city and total CO_2-emissions.

The fundamentals of the city energy model are presented in Figure 2.4.

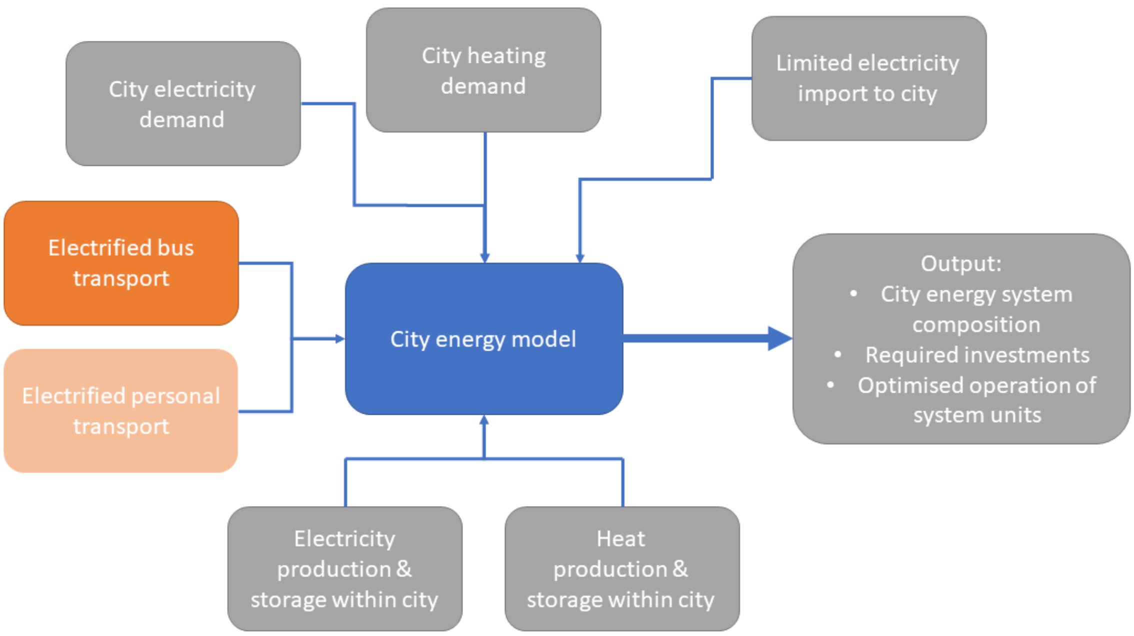

Figure 2.4: The city energy model, a simplified illustration adapted from Figure 1 in [6].

The city energy system model integrates an estimate of the hourly electricity and heat demand of Gothenburg in the year 2050. The model features both investment and dispatch of energy technologies. Heat and electricity production, with respective storage, in the city are modelled with existing capacity of the energy technologies accounted for. New capacity is added if cost-effective. Electricity and heat demand of the city are increased by 50 % from today's values to represent increases due to city growth. Import of electricity to the city is possible but limited. The price curve used for the imported electricity is based on a national system with high share of renewable generation and demand from electric cars. However, there are no limitations in the distribution capacity within the city. Export of electricity and heat from the city is not part of the model. The city energy optimisation model is based on an hourly temporal resolution. This restricts the data obtained from the EAEB model, since it contains data on every minute. The electricity demand from the buses is therefore converted to an hourly profile by adding the demand for all minutes within each hour together.

Three cases are modelled to assess the impact that electrified bus transport has on the city energy system. The following cases are evaluated:

City Only:
City without electrified buses

City Direct:
City with electrified trunk and city buses using a **direct charging** strategy

City Smart:
City with electrified trunk and city buses using a **smart charging** strategy

Modelling the energy system in conjunction with the bus network enable bus charging events to actively affect production and consequently cost of electricity. This feedback is not possible in the model presented in Section 2.2, which does not consider the impact on the energy system. Bus charging events can only be optimised hourly and in aggregate form, to reduce the computational capacity need. Optimisation on smaller timescales and individual buses is facilitated by the model presented in Section 2.2 instead. Refer to Table 2.1 for a detailed account of the cases modelled in this work.

2.3.1 Categorisation

In order to limit computational intensity, individual buses were aggregated to simplify the battery modelling in the city energy system. Figure 2.5 visualises three different levels of aggregation that can be used to describe the batteries in the bus network. Each small battery represents a bus. Buses with similar driving patterns are presented in the same colour. The first scale of aggregation is no aggregation at all, i.e. individual batteries. The categorised battery is a smaller aggregate of buses with similar patterns in driving demand. Buses belonging to the same category are driving and are parked at similar times during the day. Aggregation to a single large battery, the third scale, implies a significant loss in information.

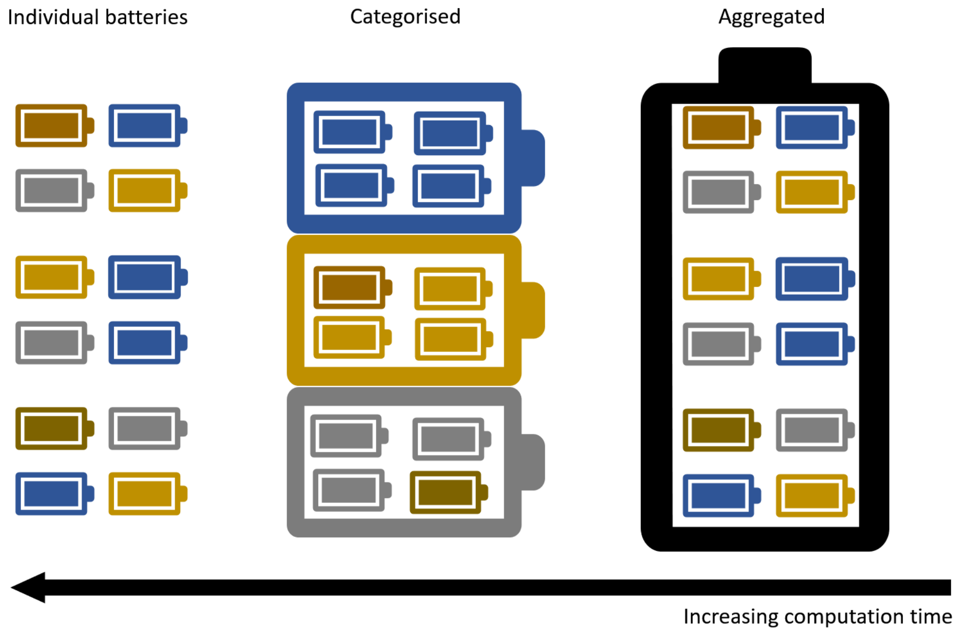

Figure 2.5: Three scales of aggregation for the battery model. Each small battery represents a bus, and the colour is a representation of its driving pattern.

The aggregated model creates fictional homogeneity since all buses inside of the battery are treated the same. This leads to *Unwanted Wireless Electricity Transfer (UWET)* between buses of the aggregated battery. UWET is a modelling error that allows for individual buses at the depot to be charging buses that are in operation. The buses in operation then have no need for charging since their batteries are charged by other buses. This occurs since they share the same aggregated battery. An illustration of this error is given in Figure 2.6. The top box represents buses that are satisfying a transport demand and consuming electricity. The demand is met by discharging the aggregated battery, as individual batteries do not exist in the aggregated model. The aggregated battery is in turn charged by the buses at the depot, seen in the lower box of Figure 2.6. The net effect of this behaviour is that depot buses are used to charge driving buses outside of their charging events.

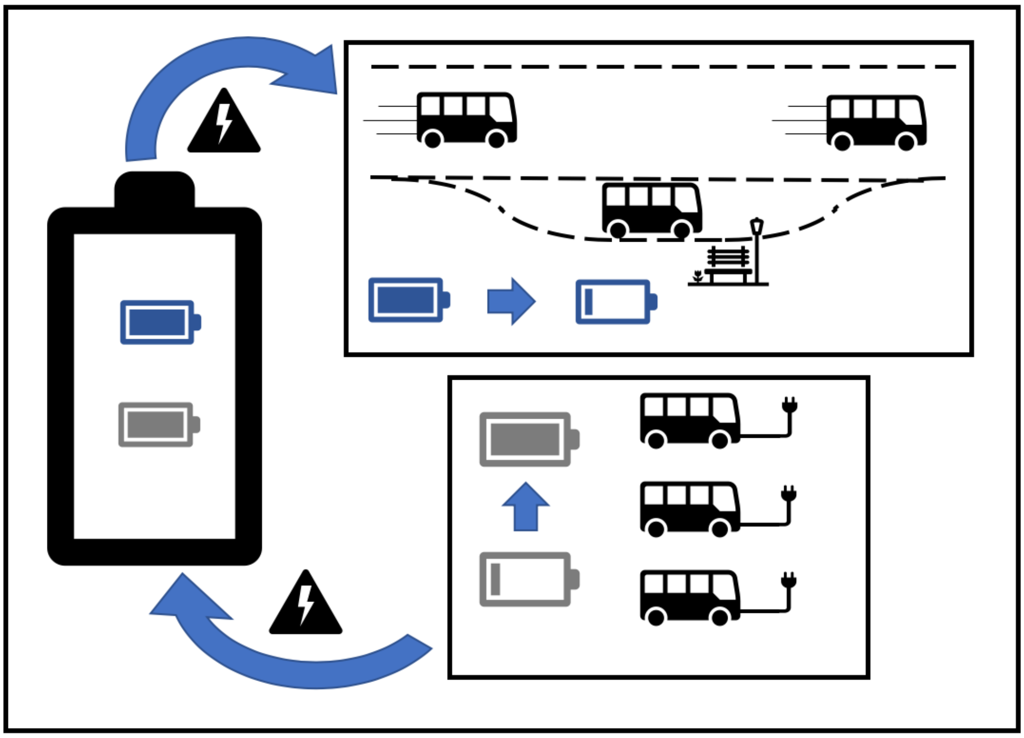

Figure 2.6: A graphical representation of the UWET issue.

To remove this error, one could simply model the individual bus batteries, however that would require multiple equations which would increase the model complexity. Instead, buses are categorised in accordance with their driving demand pattern. Consequently, buses that are available for charging during similar time frames end up in the same category.

An analysis of the electric load profiles suggest that three distinguishable categories exist: peak, middle and base type buses. This categorisation approach is used to aggregate buses in this work. Any subsequent mention of aggregation refers to this scale. The categorisation is made in accordance with Figure 2.7. The figure illustrates a load curve from electric buses that is divided into the three categories. The base category represents all buses that have less than four hours break between end of day and start of day operation. These buses are assumed to be unable to contribute with flexibility measures, since they are in near-constant operation. Buses belonging to the middle category, represent buses that have at least a four-hour break between end of day and start of day operation. These buses are expected to have some flexibility in their charging events during non-operation. The top category, peak buses, represents the buses that only operate during day-time rush hours. More specifically, peak buses are defined as buses that only operate within the confines of the largest peak of the morning and that of the evening. The definition of peak buses is that they should have more than four hours in between the working days and that there should be a gap in-between the two peaks with more than one hour of idle time. Since peak buses also travel to and from the depot during the "midday break", the depot consumption is added both to the start/end of the day and turn and return from the depot at the "midday break"

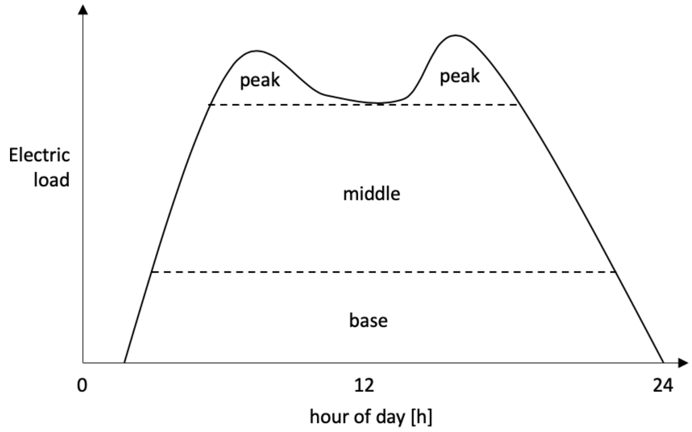

Figure 2.7: A representation of categories superimposed on the load profile of an electric bus network.

The load curve of the electric buses' changes during the weekend, from a high load to a reduced load during Friday to Sunday. This creates a surplus of buses that are not used to satisfy the driving demand. These buses can stem from every category, but predominantly from the peak category. To account for the flexibility of the buses that are off duty during the weekend, these are moved to the peak category. Only fully charged buses can be moved in this manner, as not to complicate the tracking of energy moved between categories.

Each category has its own energy balance. The main difference is that base buses are treated as a fixed load, meaning that charging events cannot be moved in time and the electricity is consumed according to the load curve. In contrast, charging of peak and middle buses is detached from the buses consumption and can occur when it is optimal, given a set of constraints. Peak and middle buses can also charge at the depot, while base buses only charge at the high-power opportunity chargers while in operation, due to their high driving demand.

The electricity demand profile is split among the categories according to Equation 2.7. The electricity demand for each *bus* and hour *t* belonging to the the same category, $Buses_{(cat)}$, is summed. The summed demand is created for each category, *cat*, where *Cat* contains all three categories (peak, middle and base).

$$\mathrm{D}_{(cat,t)} = \sum_{bus} \mathrm{D}_{(bus,t)}\ , \quad \forall\, bus \in Buses_{(cat)}, \forall\ cat \in Cat \tag{2.7}$$

The demand, $\mathrm{D}_{(cat,t)}$, of the category is equal to the sum of loads of the buses belonging to said category. To account for the fraction of buses available for charging at the depot, $\mathrm{A}_{(cat,t)}$ is determined from Equation 2.8.

$$\mathrm{A}_{(cat,t)} = \frac{\sum_{bus} \mathrm{A}_{(bus,t)}}{\mathrm{n}_{(cat,t)}}\ , \quad \forall\, bus \in Buses_{(cat)}, \forall\ cat \in Cat \tag{2.8}$$

The availability parameter $\mathrm{A}_{(bus,t)}$ is a discrete hourly parameter that is set to zero if the bus is driving, or one if the bus is available for charging at the depot. $\mathrm{A}_{(cat,t)}$

is the share of buses in each category that are available for charging at the depot. The number of buses belonging to each category is denoted by $\mathrm{n}_{(cat,t)}$. Equation 2.9 shows how the size of the aggregate battery, BS, is determined.

$$\mathrm{BS}_{(cat,t)} = \sum_{bus} \mathrm{BS}_{(bus,t)}\,, \quad \forall\, bus \in Buses_{(cat)}, \forall\ cat \in Cat \tag{2.9}$$

The categorisation procedure is only done for trunk buses. The total number of city buses is associated with some uncertainty, city buses are treated as the base category trunk buses which are represented by a fixed load profile. This is done to ensure that flexibility of city buses is not overestimated.

2.3.2 Aggregated bus battery model

The battery model in this section is created to enable the city energy optimisation model to select the most cost-effective charging of buses for the city energy system. Only buses that are classified as either peak or middle will have their charging pattern determined by the city model. Base buses only charge according to their electricity demand profile determined in Equation 2.7 and are therefore not represented by an aggregated battery.

The model features two aggregated batteries, one for the peak and middle category, respectively. The battery SoC equation is illustrated in Equation 2.10, note that only middle and peak belong to *cat* in this case.

$$SoC_{(cat,t)} = SoC_{(cat,t-1)} - D_{(cat,t)} + OC_{(cat,t)} + SC_{(cat,t)} \tag{2.10}$$

$D_{(cat,t)}$ is the driving demand of buses in category *cat* translated to electricity consumption at each hour t, OC is charging that occurs at opportunity chargers. SC represents slow charging at the depot with buses that are not currently in use. Opportunity chargers are fast chargers with high-power located at the turn-around stops of each line. These can only be used if the buses are out driving. Depot charging is a lower powered charging that only is possible when the buses are at the depot. Both OC and SC are variables in the model while D is a parameter created from the electric bus network methodology. That the battery SoC is limited by the battery size BS of the respective category, as illustrated in Equation 2.11.

$$SoC_{(cat,t)} \leq BS_{(cat,t)} \tag{2.11}$$

The SoC also has a lower limitation to represent a buffer for unforeseen events that otherwise could create situations where the buses run out of battery. The lower limit is illustrated in Equation 2.12, for both peak and middle category trunk buses.

$$SoC_{(cat,t)} \geq \max(\mathrm{D}_{(cat,t)}(t)) \tag{2.12}$$

The maximum demand during one hour of the year is set as a worst-case scenario, since if there is an unforeseen event, e.g. a power outage, the buses can still manage one hour of their maximum demand. The limitation of the slow charging rate at the depot is seen in Equation 2.13.

$$SC_{(cat,t)} \leq \mathrm{A}_{(cat,t)} * \mathrm{CP}_{(cat)} * \mathrm{n}_{(cat,t)} \tag{2.13}$$

The $CP_{(cat)}$ is in turn defined as the power of one depot charger (50 kW). Where $A_{(cat,t)}$ and $n_{(cat,t)}$, mentioned before are the fraction of buses at the depot and the total buses, respectively. Both parameters are depending on category *cat* and hour *t*.

Opportunity charging is limited to, at maximum, supplying the electricity demand of driving operation in an attempt to remove the *UWET* modelling error from opportunity charging. This prevents charging for longer duration than the gaps between trips can accommodate, preventing a violation of the bus network timetable. Equation 2.14 shows that the *OC* variable therefore cannot exceed the electricity demand from driving of the same hour.

$$OC_{(cat,t)} \leq D_{(cat,t)} \tag{2.14}$$

2.3.3 Reserve generation capacity

The electricity load profile of the bus system shows variations on a minute-basis. However, the implementation in the energy system model necessitates a temporal resolution of one hour. This electricity demand per hour is created as the average minute demand during that hour. Consequently, the peaks in electricity demand within the hour are larger than the load averaged over the hour. This phenomenon is illustrated in Figure 2.8 and the difference in electricity demand between the temporal resolutions highlighted.

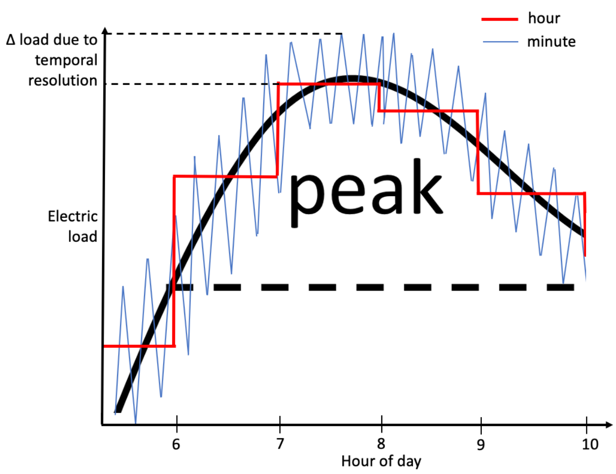

Figure 2.8: A portion of Figure 2.7 with electric load on an hour and minute scale.

A reserve in power capacity is mandated to account for the peaks in power demand that are not included when using the hourly resolution. This ensures that the energy system model invests in sufficient power capacity of electricity generating technologies that can supply quick power response. The power capacity can be supplied by either: a spinning reserve[5], available import capacity and/or a reserve

[5]Spinning reserve accounts for electricity generating units that have a spinning synchronous generator which is connected to the grid and producing electricity with less than its maximum rated power.

capacity in the stationary batteries. The generating units are not to produce more actual electricity to the system.

The reserve in power capacity of the energy system, *Reserve*, that is available at each hour t, is formulated in Equation 2.15.

$$Reserve_t \leq batt_t + import_t + \sum^{N} spin_t \tag{2.15}$$

where *spin* represents the spinning reserve of electricity producing units N. The remaining capacity of import, *import*, is determined as the difference in the maximum import capacity and actual import at hour t. Capacity contribution from the stationary batteries, *batt* is further explained in Equation 2.16.

$$batt_t = \begin{cases} \mathrm{BC} - BD_t, & \text{if}\,(\mathrm{BC} - BD_t) \leq BSoC_t * 10 \\ BSoC_t * 10, & \text{if}\,(\mathrm{BC} - BD_t) > BSoC_t * 10 \end{cases} \tag{2.16}$$

where BC represents the battery discharge capacity of stationary batteries in the energy system. BD represents the amount of electricity discharged from the batteries at hour t. The difference between BC and BD is the remaining discharge power that is available at hour t.

$BSoC$ is the state of charge of stationary batteries at hour t. The power supplied by the batteries should last six minutes, which is the average charging duration of buses using opportunity chargers. $BSoC$ is therefore converted from energy to power by multiplying it by ten[6]. Should $BSoC_t * 10$ be less than $\mathrm{BC} - BD_t$, the remaining discharge power is used. Therefore, empty batteries provide no contribution toward the capacity reserve.

The size of the reserve in power capacity that is required depends on the charging loads of the bus system, as presented in Equation 2.17.

$$Reserve_t \geq BSRR_t \tag{2.17}$$

where $BSRR$ is the *bus system reserve requirement*. The *Reserve* is set to be equal to or greater than $BSRR$ for all hours of the year. $BSRR$ depends on how the buses are charged, since opportunity and depot chargers have different charging power. This implies that direct and smart charging generate different power capacity reserve requirements. The following sections provide details on the modelling procedure for both charging strategies.

Direct charging

In the direct charging case, the electricity demand of the buses is satisfied directly by opportunity charging during the same hour. The reserve for trunk buses is represented by the combined rated power of all 26 opportunity chargers specific to trunk buses, corresponding to 11.25 MW. Since city buses have similar sized electric load peaks to that of trunk buses in the *City Direct* case, they are represented with the same combined charging capacity requirement of 11.25 MW. The $BSRR$ is therefore set to 22.5 MW at all times, which represents the maximum power required by both the city and trunk buses.

[6] MWh to MW: $\frac{60\,\mathrm{min/h}}{6\,\mathrm{min}} = 10\,/\mathrm{h}$

Smart charging

In the *City Smart* case, charging of peak and middle trunk buses can be controlled according to the energy system. The bus system reserve requirement therefore varies by category and time. The contribution from each trunk bus category and the city buses are therefore considered separately and then combined, as illustrated in Equation 2.18.

$$BSRR_t = \text{CBSRR} + \sum_{cat} (\eta_{(cat)} \cdot \eta^{opp}_{(cat,t)} \cdot \text{P}^{opp,i} + SC_{(cat,t)}), \quad \forall\ cat \in Cat \tag{2.18}$$

where CBSRR represents the reserve requirement from city buses in the form of a constant requirement of 11.25 MW. $P^{opp,i}$ is the installed capacity of opportunity chargers specific to trunk buses (11.25 MW) and $SC_{(cat,t)}$ is the rated power of depot chargers (slow chargers). $\eta_{(cat)}$ represents the share of total energy used per trunk bus category, further explained in Equation 2.19. $\eta^{opp}_{(cat,t)}$ is the utilisation factor of the opportunity chargers per category, which is explained in Equation 2.20.

Note that $SC_{(cat,t)}$ for the base category is zero at all hours, as base trunk buses cannot charge at the depot in the *City Smart* case. It should also be noted that the energy system is able to change charging of peak and middle trunk buses to accommodate the reserve requirement, should it prove cost-beneficial to do so.

Equation 2.19 illustrates the share of total annual energy used per trunk bus category, $\eta_{(cat)}$.

$$\eta_{(cat)} = \frac{\sum_t D_{(cat,t)}}{\sum_{cat} \sum_t D_{(cat,t)}}, \quad \forall\ cat \in Cat \tag{2.19}$$

where $D_{(cat,t)}$ represents the electricity demand of all buses belonging to category *cat* at hour t. Equation 2.20 represents the utilisation factor of the installed opportunity chargers for each category, *cat* and hour t.

$$\eta^{opp}_{(cat,t)} = \begin{cases} \dfrac{OC_{(cat,t)}}{D_{(cat,t)}}, & \text{if } D_{(cat,t)} > 0 \\ 0, & \text{if } D_{(cat,t)} = 0 \end{cases} \tag{2.20}$$

where $OC_{(cat,t)}$ represents opportunity charging of buses belonging to category *cat* during hour t. The limit of possible opportunity charging is given by the electricity demand as described in Equation 2.14. The utilisation factor is determined as the ratio of the utilised and possible charging.

3

Results

This chapter aims to answer research questions 1 through 3 using approaches **(i)** to **(iii)** outlined in the method. The results for **(i)** are showcased with load curves on two timescales, per hour and per minute. Results for **(ii)** are presented by the potential of individual buses to time charging events. The results from part **(iii)** focus on energy system aspects and the changes caused by the electrification of buses.

3.1 Electricity demand of Gothenburg's electric bus system

This section covers the results obtained from method **(i)**, "bus network creation and energy modelling". Important parameters of the bus network are briefly covered, followed by an overview of the buses' electricity demand.

The bus network can be characterised by the parameters presented in Table 3.1. The network features 300 buses in total, with 50 percent more city buses than trunk buses, which are spread over 38 and 8 routes, respectively. Annual electricity consumption is 20 percent higher for trunk buses, yet peak power consumption is larger for city buses. It should be noted that the driving distance is based on the bee line distance between bus stops, driving distance in reality is longer.

Table 3.1: Bus network key parameters.

	Unit	Trunk buses	City buses
Number of routes		8	38
Number of chargers		26	78
Number of buses (12 m | 18 m)		40 | 90	131 | 63
Annual electricity consumption	GWh	28.8[1]	24.1
Peak power consumption	MW	7.67	8.68
Annual driving distance	km	9 160 000[1]	9 308 000
Average electricity consumption	kWh/km	2.8[2]	2.3[2]

[1] includes trips to and from depot

[2] incl. auxiliaries, excl. charging losses. The actual consumption varies with time

A load curve can be used to represent how the electric load of all chargers varies with time. The load curve of trunk buses on a weekday is illustrated in Figure 3.1. The blue line shows the load per minute, the load per hour is shown in red. Two peaks in load are observable; one occurs in the morning between 8 and 10, the other in the evening at 18. This behaviour is reflected in both time resolutions and the general shape of both curves over the day is also similar. Nevertheless, there are also noticeable variations in load due to charging activity on the minute scale. The hourly load curve does not capture peaks and valleys occurring at the smaller timescale. Both curves show a reduction in load during the middle of the day and vastly reduced activity in late evening and nighttime.

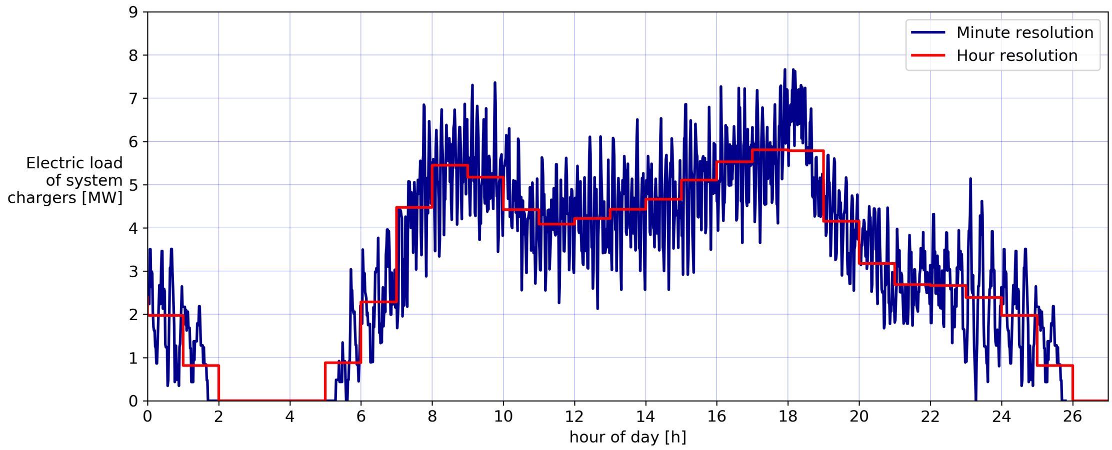

Figure 3.1: Load curve for all trunk buses electrified, without additional consumption from depot trips. The red line represents the load for each hour, the blue line for each minute.

The load curve of city buses during a weekday is illustrated in Figure 3.2. Overall, the load curve of city buses is similar to that of trunk buses. However, the differences in load between minutely and hourly curve are larger for city buses compared to trunk buses. The variance in load of the minute scale is also larger in the case of city buses. Even though the network consists of considerably more city buses than trunk buses, the electricity demand is similar. The driving demand is the deciding factor in determining the electricity demand, whereas the number of buses only affects how the driving demand is divided among the bus fleet.

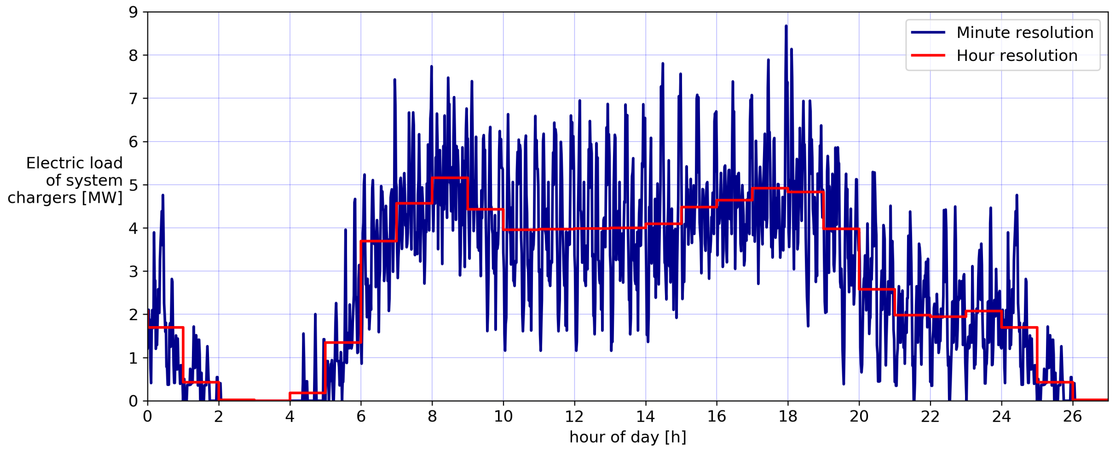

Figure 3.2: Load curve for all city buses electrified, without additional consumption from depot trips.

The combined load curve for trunk and city buses during a weekday is presented in Figure 3.3. Note the change in scale of the y-axis compared to Figures 3.1 and 3.2. Peak power consumption is around 15.5 MW on the minute basis, while the hourly curve features two peaks of around 11 MW. A smoothing effect on the variations in load on the minute scale can be observed. The gaps in charging are filled since charging events of the two classes of buses do not always overlap in time.

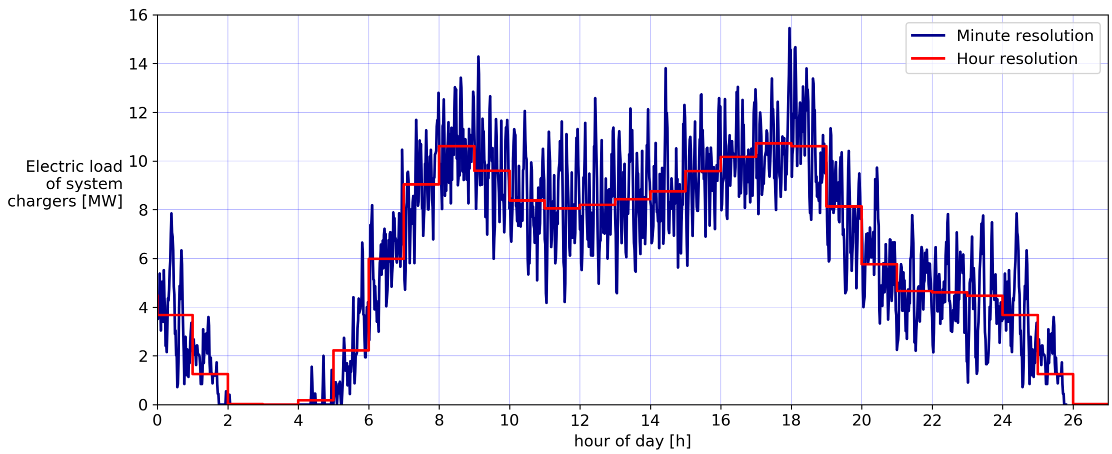

Figure 3.3: Load curve for all buses electrified, without additional consumption from depot trips.

The combined hourly load curve for trunk and city buses over an entire week is presented in Figure 3.4. The weekly curve does not contain the high minutely variations of the load curves presented before since the curve is presented on an hourly scale, the high peaks are therefore averaged out. It is apparent that the peaks correspond to the peaks in Figure 3.3 and we see variations in load from 11 MW to no load during nighttime. There is a reduction in load during the weekend, and there is a change from two peaks of 11 MW during the weekdays to one peak around 7 MW during each of the two days of the weekend. Weekdays have the same load profile, as their driving demand is identical. Saturday and Sunday are different to both each other and to the weekdays.

While delays in the timetable can affect the timing of driving demand within the hour, electric load should remain similar when evaluated on an hourly timescale. Therefore, the electricity demand of buses can be regarded as somewhat predictable given that the bus timetable does not change frequently. A margin of error on the minute scale exists and it is likely to be affected by the aforementioned delays. The additional consumption from depot trips is not included in any of the Figures 3.1 through 3.5.

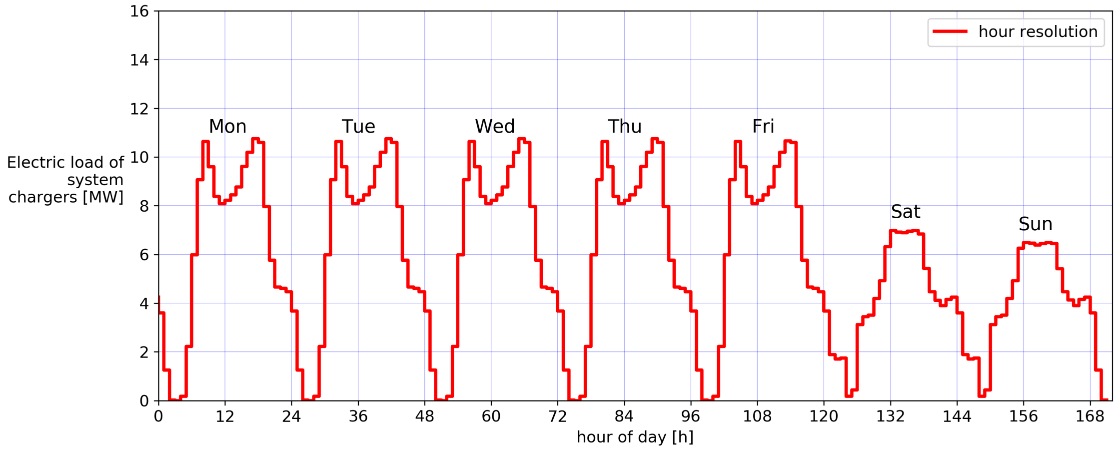

Figure 3.4: Hourly load curve over a week for all buses, without additional consumption from depot trips.

Figure 3.5 illustrates the normalised electricity demand of buses and of the city of Gothenburg on Tuesday, February 8, 2050. While the city electricity demand does not decrease as dramatically during nighttime, a clear correlation between the two demands is visible. Both demands are significantly higher during daytime, with peaks in the afternoon. The electricity demand of buses features two peaks with a valley between, whereas that of the city has one peak in the afternoon. Nevertheless, electrification of buses in this manner will lead to an increase in total electricity demand where it is already at its highest.

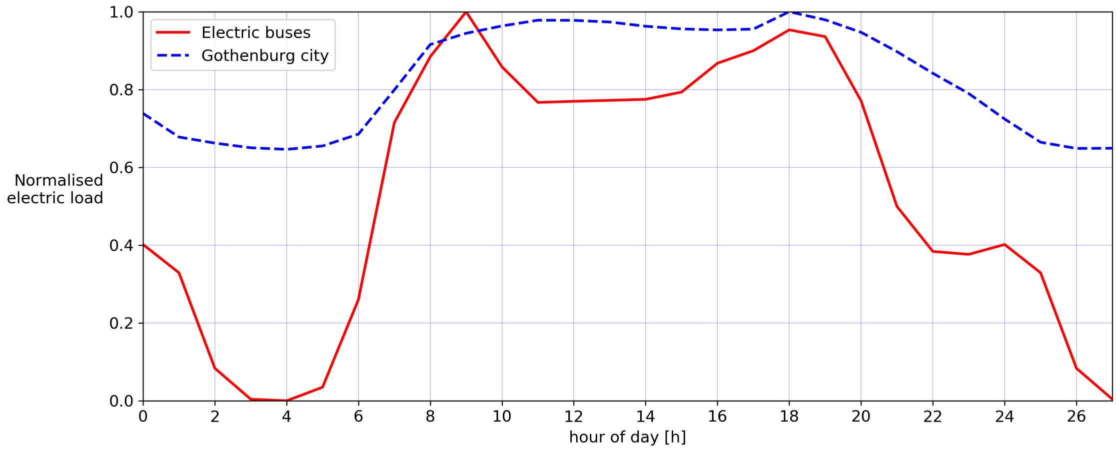

Figure 3.5: Load curve for all electrified buses together with the city electricity demand. The loads are normalised to their corresponding max load.

3.2 Bus scale optimisation of charging

This section presents the results from the bus scale optimisation, part **(ii)** of the method. The charging of buses is optimised on an individual level and the individual charging loads are summed together, to study the effect the individual optimisation has on the entire bus network. This enables a comparison between this model and the (aggregated) city model. First, cost savings from smart charging are presented for three time-periods: one week in summer, one week in winter and an average of 52 weeks. Then a closer look is taken at the charging pattern that results from the cost minimisation. The limitations and utilisation of flexibility in charging are examined.

Table 3.2 illustrates the charging costs for smart and direct charging in the form of an average electricity consumption cost. Two three-day periods, representing summer and winter, are considered, and presented together with respective cost savings from smart charging. The cost savings from smart charging correspond to 26 % of the direct charging costs in the summer and 8 % in the winter. Cost savings in absolute terms are similar for both cases. In an attempt to obtain a representative charging costs, 52 three-weekday periods were modelled together with the electricity cost curve of the entire year. To simplify the model, the included results only use bus related data for Tuesdays, Wednesdays and Thursdays. These days were selected since driving demand and availability is the same for all three days. Over the period of a year, smart charging leads to a reduction in charging cost of around 13.5 % compared to direct charging.

Table 3.2: Average electricity consumption cost with a smart and direct charging strategy, for a summer and winter period and averaged over 52 weeks.

Model	Unit	Average electricity consumption cost	Saved compared to direct charging
Smart (three days in summer)	€ MWh^{-1}	24.6	8.2
Direct (three days in summer)	€ MWh^{-1}	32.8	-
Smart (three days in winter)	€ MWh^{-1}	93.1	7.9
Direct (three days in winter)	€ MWh^{-1}	100.9	-
Smart (52 3-weekday periods)	€ MWh^{-1}	65.8	10.3
Direct (52 3-weekday periods)	€ MWh^{-1}	76.1	-

Details on the charging operation are presented in Figure 3.6. The modelled period spans three sunny days, 3/7 to 5/7. Panel a) illustrates the charging load and summed battery SoC of all buses in the *Bus Smart* case. The charging load of the *Bus Direct* case is featured in panel b). The marginal electricity cost curve for the same days is shown in green in both panels. It is taken from a city energy system with an annual electricity generation share of 27 % from solar PV. High solar PV generation is the main reason for the dips in marginal electricity cost during the summer period. The frequent variations in the load stem from a time resolution of one minute illustrated over a period of three days.

In the *Bus Smart* case, charging activity is shifted to low electricity cost hours, typically reaching maximum charging capacity around noon. The summed battery SoC never reaches zero but is limited by the SoC-constraint of the individual bus batteries. The battery of each individual bus is not allowed to be discharged below 20 % SoC, which translates to around 8 MWh of summed SoC.

Direct charging occurs during both high- and low-cost hours as it cannot be changed by the model. The afternoon peak in direct charging coincides with the daily peak in electricity cost.

During the summer, the first peak in driving demand coincides with low electricity prices caused by significant solar PV generation. The driving demand is roughly proportional to the direct charging profile seen panel b).

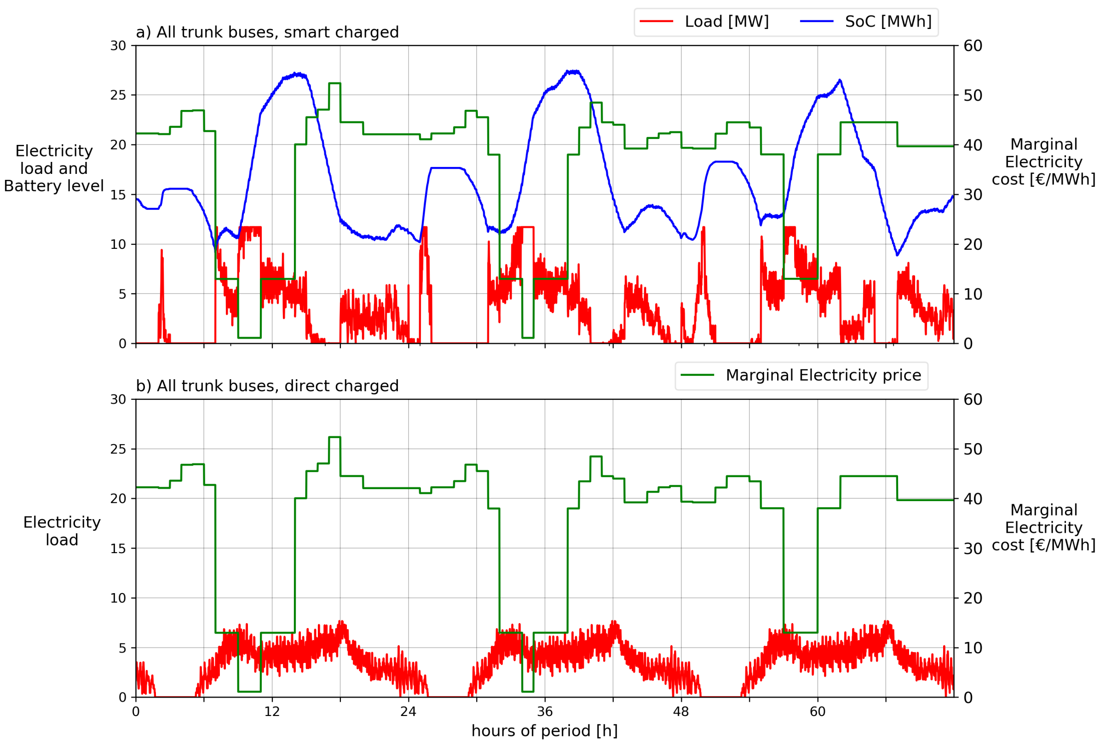

Figure 3.6: Details of charging operation for all trunk buses during three days of summer, using smart charging a) and direct charging b).

The same modelling procedure is employed for three winter days, where the electricity cost shows less variation during the day. The results are illustrated in Figure 3.7, where the optimised days span from the 9/1 to the 11/1.

Like the summer period, smart charging is more pronounced during hours of low electricity cost, which is reflected in the high load and increasing SoC in panel a). However, compared to the summer period, the marginal electricity cost has lower intra-daily variance in the winter and the charging occurs over longer periods of time but with lower charging power.

There are also fewer hours with no charging load, even if the electricity cost periodically is high. The high-cost event at the end of the period exemplifies this. Smart charging still does take place during that time, even though it is expensive to charge. Certain buses have a high driving demand and therefore need to charge during these high-cost hours, irrespective of the cost during the period. For both the summer and winter period, smart charging is increased before and reduced during the high-cost hours but can never be prevented entirely.

Similar to the summer period, the peaks in direct charging occur during the same time as the peaks in marginal electricity cost. Note the difference in scale for the electricity cost when comparing Figure 3.6 and 3.7.

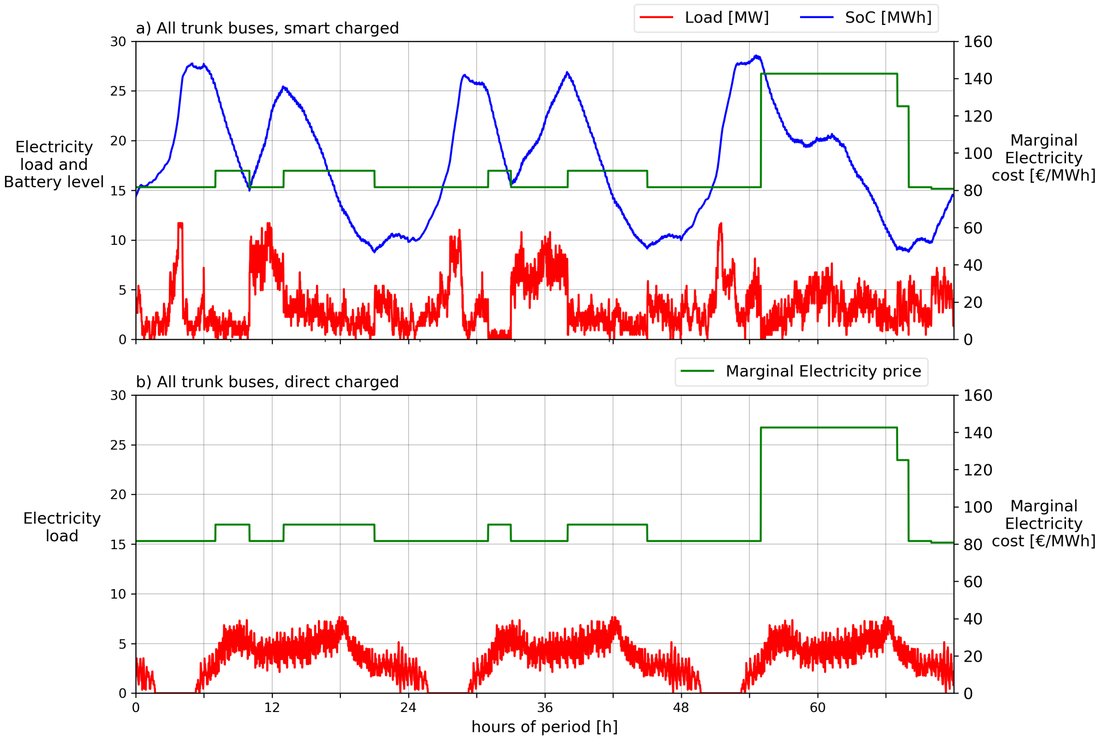

Figure 3.7: Charging of all trunk buses during three days of winter, a) smart charging and b) direct charging.

3.3 City energy system optimisation model

This section presents the results of the energy system optimisation model, part **(iii)** of the method. First, the three trunk bus categories are presented with their corresponding annual energy consumption. Then, the results from the *City Only*, *City Direct* and *City smart* cases are presented and compared. Dispatch and investment of energy technologies, bus charging patterns and the electricity mix of bus-charging are assessed. Lastly, the effect of the reserve power requirement on dispatch and investment of technologies in the energy system is evaluated.

3.3.1 Categorisation

The following results correspond to part **(iii a)** of the method. Each trunk bus belonging to the network is assigned to one of three categories: base, middle or peak. The categories serve as a basis for aggregation and are used to account for differences in individual driving patterns between buses. City buses are not categorised.

Table 3.3 illustrates how the bus network is divided between the categories. Half the number of trunk buses belong to the middle category with the remainder split almost equally over the peak and base category. However, the peak buses make up only a tenth of the trunk buses total electricity consumption, while base buses consume a bit more than a third. The intensity of use, in the respective categories, is reflected in the number of battery cycles per year; where base has the highest number, followed by middle and lastly peak. The battery cycles are calculated on the aggregated battery and is analogous to the average battery cycle of the individual buses within the aggregate.

The data from trunk buses presented in this chapter includes energy consumption caused by trips to or from the depot. The categorisation is used to assign the frequency of said trips. Base and middle buses make the trip twice a day, at the beginning and end of daily operation. Peak buses make the depot trip four times a day, due to the two additional trips during the midday break.

Table 3.3: Breakdown of the categorised bus network.

Parameter	Unit	Trunk buses	City buses
Peak buses electricity consumption	GWh/year	3.4	0
Middle buses electricity consumption	GWh/year	14.5	0
Base buses electricity consumption	GWh/year	10.9	24.1[2]
Whereof consumption from depot travel	GWh/year	2.4	0[1]
Number of peak buses		40	0[2]
Number of middle buses		60	0[2]
Number of base buses		30	194[2]
Annual battery cycles, peak buses	full cycles/year	330	0[2]
Annual battery cycles, middle buses	full cycles/year	883	0[2]
Annual battery cycles, base buses	full cycles/year	1327	534[2]

[1] Depot travel consumption is not determined for city buses

[2] City buses are not categorised and therefore placed as a fixed load together with the base category

The load curve for trunk buses divided into the three categories is illustrated in Figure 3.8. Base buses are in operation during almost all day and their load is almost the same over all hours. Most of the middle buses operate from 06:00 to 22:00 and constitute the largest power and energy use over the day. Peak buses operate primarily from 07:00 to 11:00 and 14:00 to 19:00, using the least energy daily.

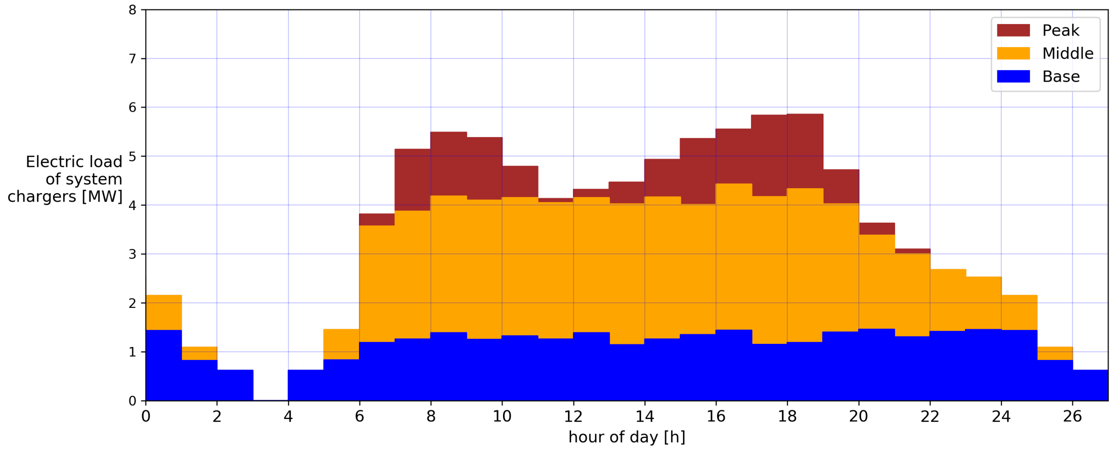

Figure 3.8: Weekday load curve for trunk buses, coloured according to category.

The load and categorisation are changed during the weekend due to a reduction in the bus driving demand. The weekly categorised load is represented in panel a) of Figure 3.9. When the buses are at the depot they are classified as being available and assumed to be connected to charging infrastructure. The share of buses available for middle and peak category trunk buses is illustrated in panel b) and c) respectively.

Base trunk buses are assumed to have no available time for depot charging since they have less than four hours without demand each day. Base bus load is near constant for all hours of the week, with a slight increase on Fridays. The increase stems from elevated nighttime driving demand between Friday and Saturday. This leads to less time between end and start of day operation and consequently more buses are classified as belonging to the base category.

During weekends, operation of middle buses is reduced, and peak buses have no transport demand at all. The instances of peak category load during the weekend are caused by middle buses changing category at the depot after daily operation. The electricity consumed by middle buses from depot travel can first be supplied at the depot and is consequently registered as charging of peak category buses. However no peak buses are in operation, as seen in the availability over the same period.

During the weekend, the availability for middle buses is increased and that of peak buses constantly equal to one. For weekdays, middle and peak buses are mostly available during the night. Peak buses differ in that they also have high availability in the middle of the day, between 10:00 to 14:00. The pattern for load and availability is repeated over the weekdays and only differs for peak and middle buses during the weekend.

Any differences in the load profile presented in Figures 3.8 and 3.9 to that shown in previous figures is due to the addition of depot consumption and category transfers of buses.

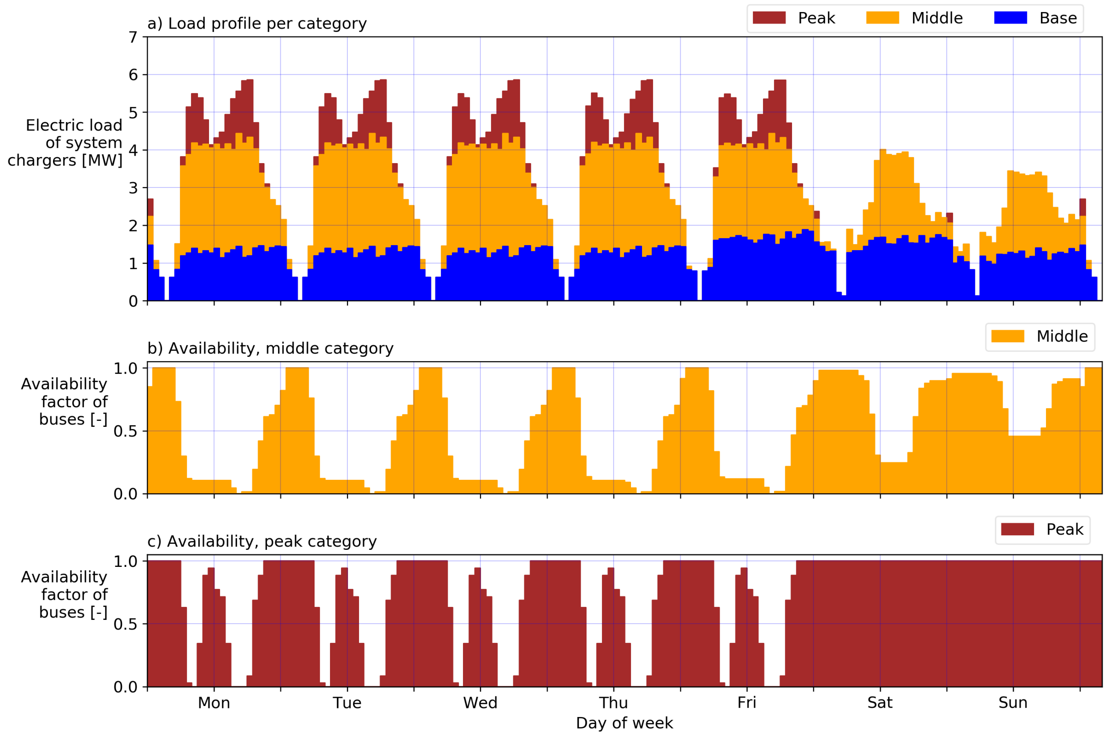

Figure 3.9: Weekly availability and load profile of trunk buses according to category.

3.3.2 Comparison of cases in the optimised city energy system

This section covers the optimised city energy system, part **(iii b)** of the method. Three different cases are modelled: *City Only*, *City Direct* and *City Smart*. This section presents the differences between these cases.

The most significant parameters of the energy system and buses are presented in Table 3.4. It is found that electric buses make up less than one percent of the total electricity demand in the city. Therefore, only subtle changes in the parameters describing the energy system are observed.

Minor changes in the electricity demand of the city and power-to-heat (PtH) technologies can be observed between the modelling cases. Small changes in investment into stationary batteries and solar PV are also observable, as are changes in curtailed electricity and import.

Total energy system cost (consisting of investment and dispatch cost) increases when introducing electric buses. The *City Direct* case results in higher cost than *City*

Smart. It can also be noted that the smart charging buses seem to reduce the need for stationary batteries in the electricity system compared to the direct charging case. In the *City Smart* case, installed capacity of stationary batteries is reduced by 20 MWh, which can be compared with the available bus battery capacity for smart charging of 22 MWh.

The results show that electric buses could aid the expansion of solar PV in the city context. The electricity demand added to the system by electric buses is largely satisfied by domestic generation. The increase by 52.9 GWh is met by an increase in solar PV generation by 32 GWh and 10 GWh in CHP generation. The remainder is accommodated by a reduction in PtH demand and an increase of imported electricity. Note that most of the electricity consumed within the city still is imported from outside of the city energy system.

Bus charging cost is reduced for smart charging compared to direct charging. The bus charging cost is calculated from hourly charging load and marginal electricity cost.

Table 3.4: City model parameters for the three energy system cases.

Parameter	Unit	City Only	City Direct	City Smart
Electricity demand, city (excl. PtH & buses)	GWh/year	6131	6133	6132
Electricity demand, PtH	GWh/year	696	689	687
Electricity demand, buses	GWh/year	-	52.9	52.9
Storage capacity of stationary batteries	GWh	1.10	1.15	1.13
Installed solar PV	GW	1.81	1.85	1.84
Curtailed electricity	GWh/year	56.81	60.79	61.08
Solar PV electricity generation	GWh/year	1845.1	1879.8	1875.4
CHP electricity generation	GWh/year	569.2	580.9	581.7
CCGT electricity generation	GWh/year	42.4	42.4	42.3
Domestic electricity generation	GWh/year	2456.7	2503.1	2499.4
Imported electricity	GWh/year	4370.8	4371.0	4372.3
Energy system cost	MEUR	418.3	421.7	421.6
Average marginal electricity cost	EUR/MWh	66.55	67.15	67.11
Bus charging cost	MEUR/year	-	3.74	3.58
Bus charging cost	EUR/MWh	-	70.62	67.75

The charging profiles for the *City Direct* and *City Smart* cases are shown in Figure 3.10. Panel a) features the load curves of direct and smart charging and illustrates fixed and flexible parts of the latter. Panel b) and c) show the respective load curves together with solar PV generation. The period covers Saturday, March 5, to Sunday, March 13, 2050.

Even though the system has the possibility to decide when charging takes place in the smart case, the general shape of both load curves is similar. The load is comparable for both cases except for weekends, where smart charging takes place earlier to match PV generation.

The direct charging pattern is dictated by the driving demand given from the timetable. Therefore, only four distinct charging patterns exist: Monday through

Thursday, Friday, Saturday, and Sunday. The direct charging demand is the same for each week of the year.

Smart charging shows no identical repetition like direct charging, although some patterns can be observed. Peaks in smart charging load occur at the same time as peaks in solar PV generation, generally right before noon. Smart charging shows higher frequency of load variations than direct charging and unlike the *City Direct* case, charging also takes place during nighttime. The valleys in direct charging load around noon are not present when smart charging since smart charging maximises the usage of cheap electricity from solar PV generation during noon. However, a considerable amount of direct charging happens to take place at the same time as PV generation, whereas smart charging actively favours charging during hours with high PV generation.

The charging load for all buses is shown in Figure 3.10. The model can only change the charging pattern of trunk peak and trunk middle buses in the smart case, as illustrated by the flexible part in panel a). The charging of the remaining buses is unchanged, even in the smart charging case, as indicated by the fixed charging load. It is likely that smart charging would result in a larger peak during the noon if the share of flexible charging is increased. It should also be noted that the power of peaks in PV generation are an order of magnitude larger than that of bus charging.

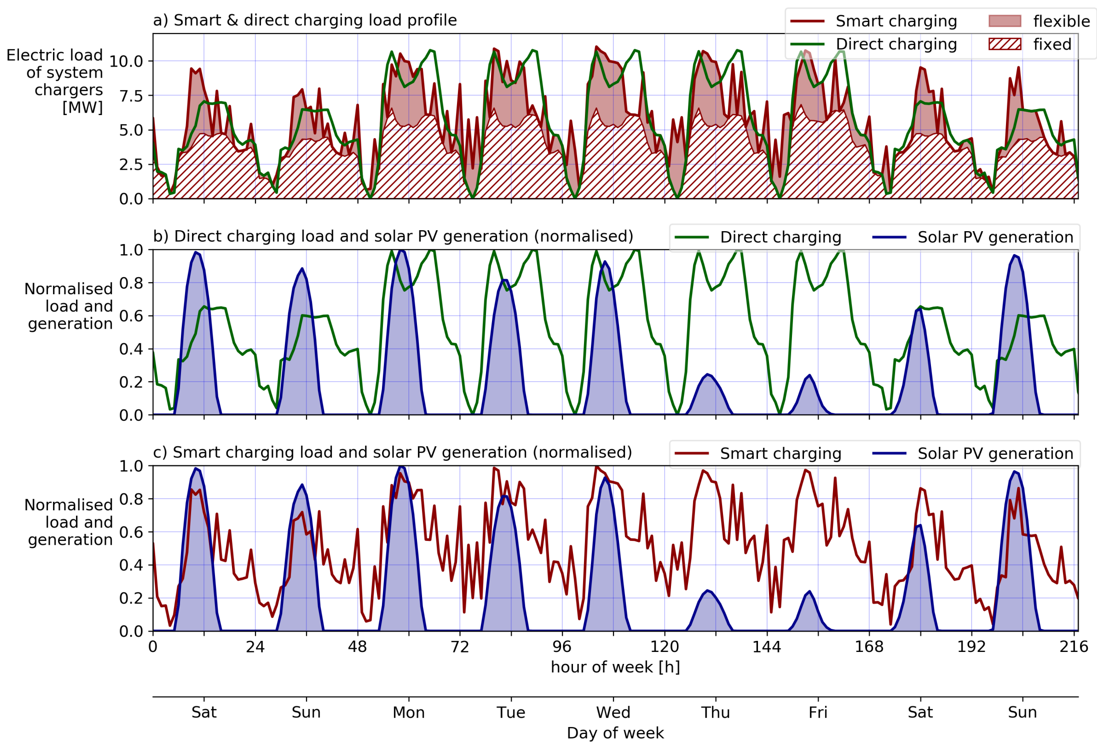

Figure 3.10: Load curves of buses for direct and smart charging with fixed and flexible load illustrated in a) from Saturday, March 5, to Sunday, March 13, 2050. Both charging strategies are shown together with solar PV generation in b) and c) respectively.

The charging pattern of trunk peak buses for the *City Smart* case is illustrated in Figure 3.11. Panel a) shows utilised opportunity charging together with the possible charging. The possible charging is given by the constraint that opportunity charging cannot charge more than discharged by the driving demand, as illustrated by Equation 2.14. Depot charging is featured in panel b), aggregated battery size and state of charge in c) and marginal electricity cost inside the city in panel d). The period covers Saturday, March 5, to Sunday, March 13, 2050.

The load of opportunity charging, and depot charging is on the same order of magnitude. However, more energy is transferred through depot than opportunity charging during the period. Two periods with repeating patterns can be discerned in panels a) and b): weekdays and the weekend. During weekdays, more electricity is charged at the depot than at opportunity chargers. Charging occurs mostly around noon but also during early morning. For hours with low electricity cost, charging is considerably higher than otherwise and often the full charging capacity is used. Charging on weekends takes place solely during low electricity cost hours, as peak buses do not need to fulfil any driving demand and instead are able to charge opportunistically. It should be noted that the model has knowledge of all future electricity costs, facilitating charging optimisation that PTOs likely cannot replicate. No opportunity charging of peak buses occurs during weekends since the buses are parked at the depot.

The changes in battery size in panel c) are caused by buses switching categories, adding, or removing battery capacity from the category. The SoC changes correspondingly since only fully charge buses can be added or removed to a category. The aggregated battery is charged fully around noon on weekdays, discharged during the afternoon and not charged again until nighttime or the next morning. Prior to high-cost hours, the battery is charged fully. Note that the SoC of the aggregated battery never falls below the minimum required SoC of 1.6 MWh.

To replicate this charging strategy, PTOs are required to have detailed information of electricity costs for the nearest 48 hours. The electricity cost is generally highest during the afternoon on weekdays, while the lowest costs occur around noon on weekends. The high variation is caused by a large share of electricity generation stemming from solar PV, which is a rather predictable variation on a city scale.

It should be noted that the period only represents roughly two percent of the entire year. No two weeks are the same, and the patterns observed during this period need not be the same either. However, the period is chosen as it best captures the operational details of peak trunk buses. No significant discrepancies are observable during other periods of the year.

Still, the most significant factor for determining the charging pattern of trunk peak buses is the electricity cost. Whether opportunity charging or depot charging is used depends on the availability of the charging type during low-cost hours.

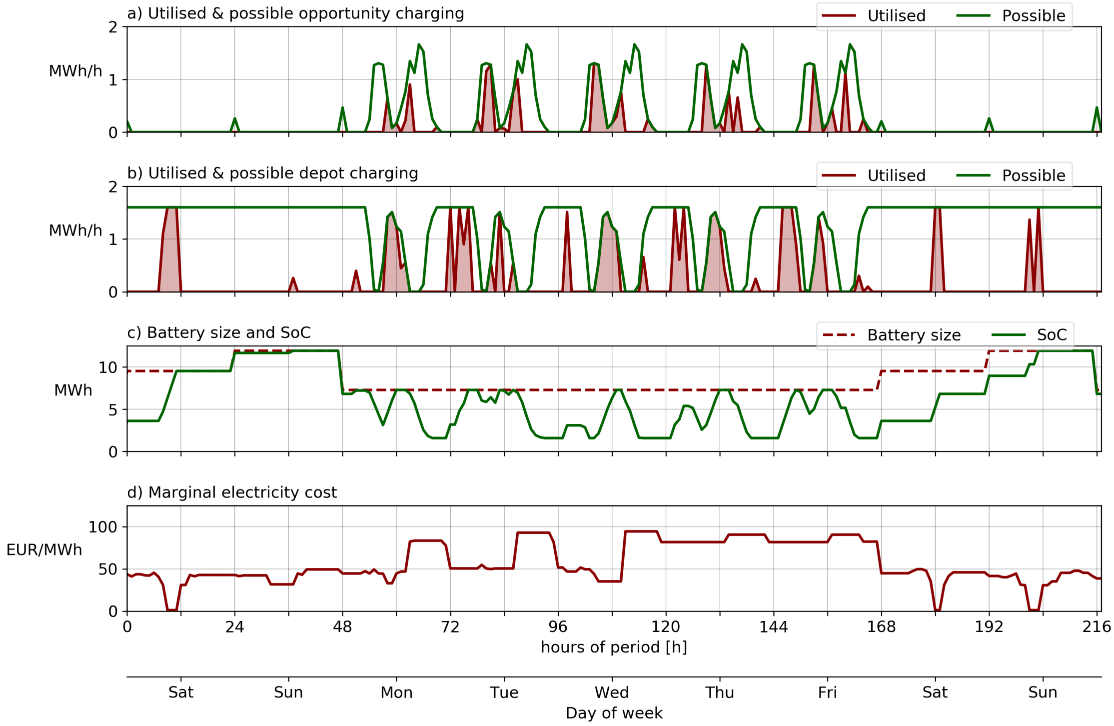

Figure 3.11: Parameters pertaining to the operation of trunk peak buses in the *City Smart* case from Saturday, March 5, to Sunday, March 13, 2050.

The charging pattern of trunk middle buses for the *City Smart* case is illustrated in Figure 3.12. The time period and details shown are the same as that for the trunk peak buses in Figure 3.11. In general, Monday through Thursday follow similar charging patterns. The charging activity is increased in the morning and around noon. Compared to the weekdays, electricity use is reduced during Friday to Sunday. Panel a) shows that opportunity charging is the predominant charging method during the hours around noon. Most of the charging for middle buses takes place in this manner. Panel b) illustrates that the depot charging on weekdays is primarily available at night and early mornings with an overall higher availability during weekends.

Panel c) shows that the aggregated battery is charged fully shortly after noon on weekdays, discharged during the afternoon and not charged again until nighttime or the next morning. However, note that buses in operation are charged by opportunity charging during their time of operation, as seen in panel a). Note that the SoC of the aggregated battery never falls below the lowest allowed capacity of 3.2 MWh. Again, changes in battery size are caused by buses switching categories, adding or removing battery capacity from the category. At hour 144, buses are transferred to the base category, and at hour 168 middle buses that are not used during the weekend are transferred to the peak category.

An indication of the *UWET* modelling error can be observed at hour 44. Driving demand is approximately 0.7 MWh/h, as indicated by the potential for opportunity charging in panel a). No opportunity charging is taking place and 2 MWh/h are being charged to the aggregated battery from the depot. Prior to hour 44, the SoC is at the lowest allowed level, meaning that it cannot supply electricity to driving buses during hour 44. Instead of using the opportunity charger, driving buses use the electricity in the aggregated battery which is solely supplied by depot charging during this hour. In total, this error only accounts for 3 % of all charged electricity to middle and peak buses and occurs during 600 hours of the year.

Multiple distinctions between trunk peak and middle buses can be noted, paramount are the charging loads seen in panel a) and b). The hourly load is generally twice as large, and the total charged electricity is higher in the middle category. The driving demand or discharge rate of the aggregated battery is considerably larger for middle trunk buses, as seen in panel c). Charging activity is higher during high cost hours in the case of trunk middle buses.

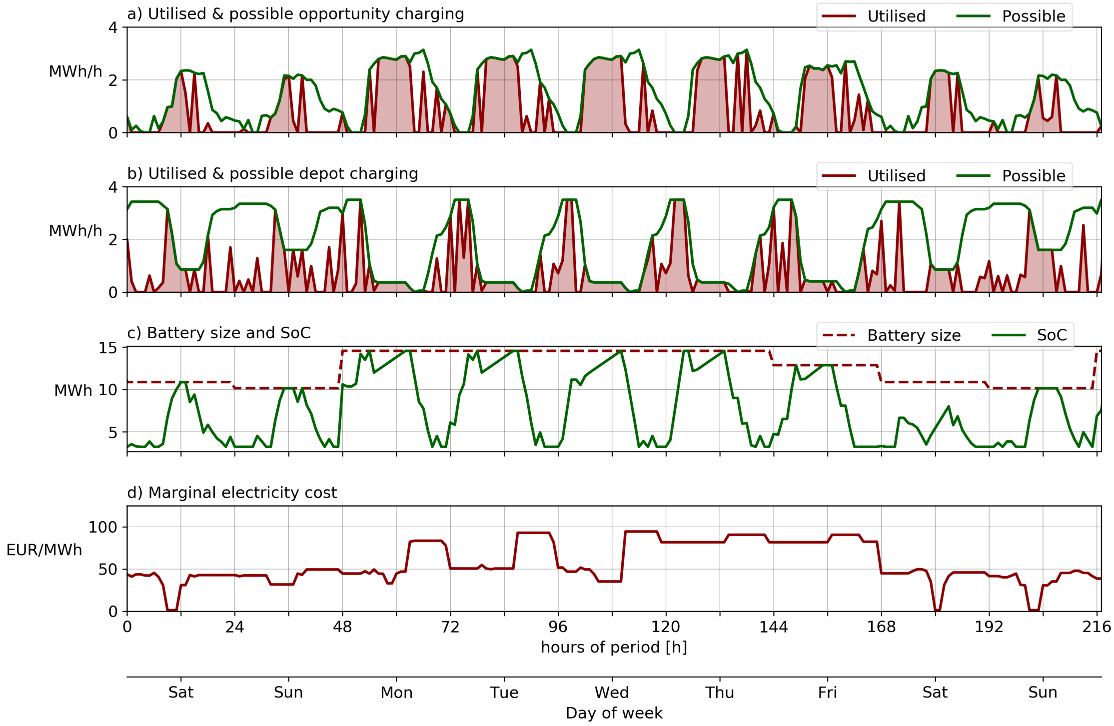

Figure 3.12: Parameters pertaining to the operation of trunk middle buses in the *City Smart* case from Saturday, March 5, to Sunday, March 13, 2050.

The charging pattern of trunk buses for both the city model and the bus scale model are illustrated in Figure 3.13. In panel a), charging patterns from the *City Direct* and *City Smart* case are illustrated. It is noted that the afternoon peak in charging in the *City Direct* case is reduced in *City Smart* by increased charging before and after the peak.

The charging pattern of trunk buses from the *Bus Smart* case, in which the charging operation of each individual bus is optimised (Section 3.2), is presented in panel b). The charging is similar to that of *City Smart*, however, the load is generally higher and more concentrated in time. The charging reaches maximum power between 10:00 and 11:00 and the there is no charging right before 18:00.

Electricity generation from solar PV within the city is illustrated in panel c). A correlation between the peaks in charging load of both *Smart* modelling cases and the generated electricity from solar PV can be observed. Charging in *Bus Smart* is concentrated even further around the peak in solar PV generation than that of *City Smart*. Note that the bus scale model is only indirectly "aware" of the solar generation since it reacts on a margin electricity cost curve. It is worth noting that the bus scale model optimises the use of the opportunity chargers, allowing it to use the full power of all installed opportunity chargers. In contrast, the city model is limited to at most charging the driving demand within the same hour.

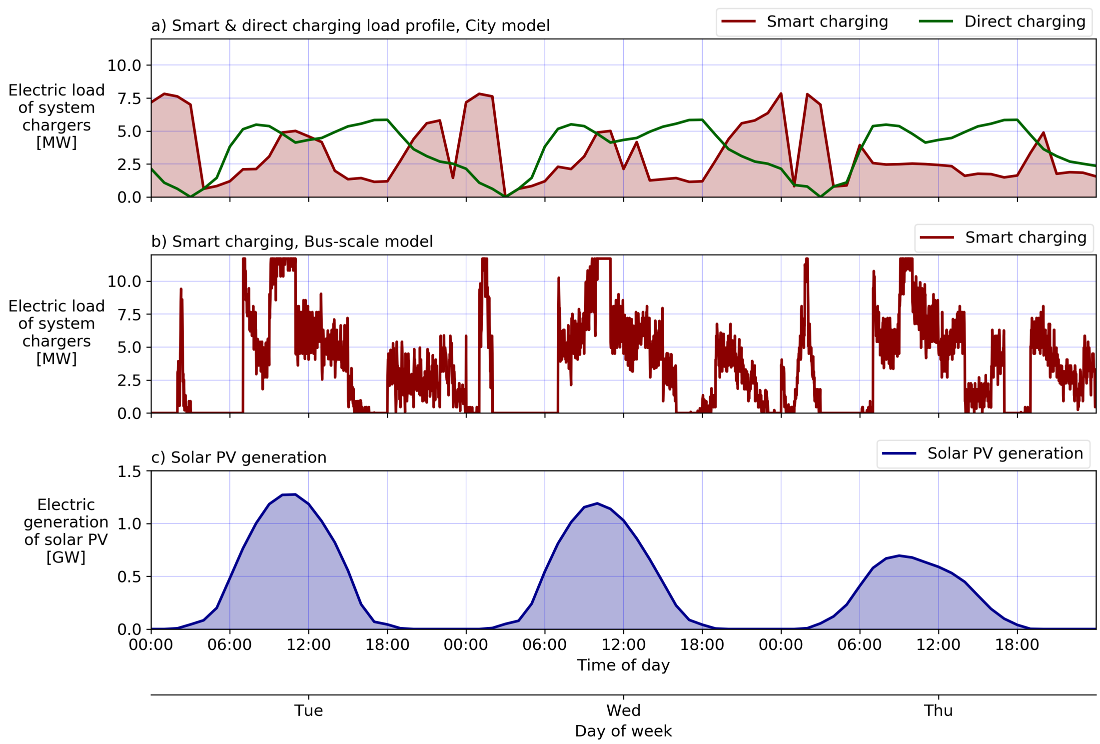

Figure 3.13: Comparison between the trunk buses in the city model and the bus scale model together with solar generation, on 5 July 2050

The electricity mix used by the buses and the city is listed in Table 3.5. The cases *City Only*, *City Direct* and *City Smart* are compared. Most of the electricity used in the city is imported while the largest share of domestic generation stems from solar PV. Introduction of electric buses to the city results in the share of solar PV generation increasing by 0.3 PP and CHP by 0.2 PP, at the expense of imported electricity. This is mainly the result of additional investments in said generation technologies leading to higher annual domestic generation. Note that even though the share of import has decreased, the actual amount of import has increased.

There is a distinction to be made between the electricity used by buses and that used by the city. Electricity consumed by buses features a higher share of solar PV than that consumed by the city. Smart charging of buses increases the PV share of buses further. It should be noted that the electricity mix of the buses is calculated without accounting for the actual electricity mix of charging from stationary batteries. This could increase the share of solar PV further, as the stationary batteries are charged by an electricity mix of 50 % solar PV on average.

The electricity mix for charging of buses is similar for the *City Direct* and *City Smart* case. This indicates that the charging load of buses coincides well with solar PV generation even without smart charging. However, only 34 % of the bus electricity demand can actually be changed in the *City Smart* case as indicated by Table 3.3 and Figure 3.10. The electricity mix of trunk peak buses consists of 44.6 % solar PV, suggesting that higher PV shares may be possible if more of the bus electricity demand could be moved by the model.

Table 3.5: Electricity mix for the city and the charging of buses for the three city modelling cases.

Results	Unit	City Only	City Direct	City Smart
Solar PV electricity generation	%	27.0	27.3	27.3
CHP electricity generation	%	8.4	8.5	8.5
CCGT electricity generation	%	0.6	0.6	0.6
Domestic city production	%	36.0	36.4	36.4
Imported electricity	%	64.0	63.6	63.6
Electricity mix for charging of buses				
Solar PV	%	-	31.1	31.7
CHP	%	-	7.7	7.5
CCGT	%	-	0.5	0.5
Import	%	-	60.7	60.3

Differences in charging load over the year are visualised by the load duration curve in Figure 3.14. It illustrates the combined charging load of buses for each hour, sorted in descending order, for both *City Direct* and *City Smart*. The maximum charging load for both strategies is around 11 MW. The charging load for smart charging is slightly lower for approximately 4700 hours, whereas it is higher for the remaining hours. The result is a flatter load duration curve. The fact that the load curves of *City Direct* and *City Smart* are so similar suggests that charging loads are only slightly changed but moved in time instead when smart charging is employed.

Direct charging results in a curve with discrete steps, otherwise the loads are of similar magnitude over the year. The discreteness of direct charging is caused by charging only occurring at either rated power or not at all, whereas smart charging can take place within the entire range. Another reason for the discrete look is that the same charging load is repeated for each week of the year.

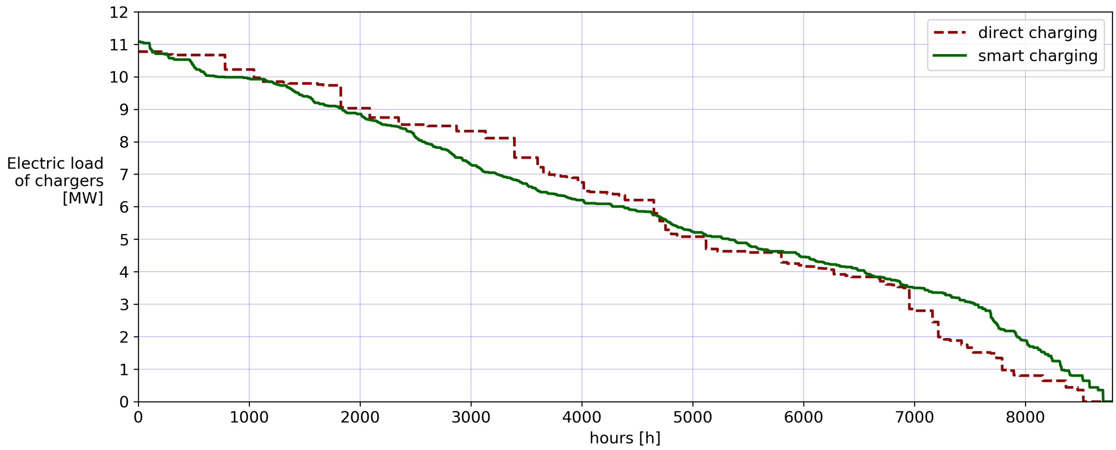

Figure 3.14: Load duration plot for direct and smart charging strategies.

3.3.3 Assessment of reserve power

To account for the intra-hourly variations in charging load, seen in Figure 3.3, the minute scale charging load is incorporated in the city model in the form of a power reserve requirement from buses, termed $BSRR$ as presented in Equation 2.17. This section evaluates the effect of said power reserve requirement on the charging pattern of buses as well as the dispatch and investment of the city energy system.

Differences in a selection of energy system parameters due to $BSRR$ are presented in Table 3.6 for the *City Direct* and *City Smart* modelling cases. The same case with and without the power reserve requirement are compared to study the effect it has on the city energy system. The units in this table differ, compared to previous tables, to highlight the changes. The values in the table are not absolute values but differences between a case with $BSRR$ and a case without.

The $BSRR$ affects the dispatch and investments of the energy system differently between the two cases. In the *City Smart* case, the reserve requirement decreases the amount of installed solar PV, while it slightly increases the installed capacity in CHPs. In contrast, investments in solar PV capacity increase when $BSRR$ is imposed on the *City Direct* case. The difference in solar PV investments between *City Direct* and *City Smart* could be explained by the difference in installed capacity of stationary batteries. The increased storage capacity in the batteries in primarily used to satisfy the $BSRR$, as is later illustrated in Figure 3.16. Batteries and solar PV act symbiotically, where an increased capacity of stationary batteries can facilitate higher cost-efficient installed solar PV capacities. However, it is worth noting that the differences caused by the power reserve requirement are negligible when compared to the system scale (see Table 3.4).

Bus charging cost is reduced with $BSRR$ in the *City Smart* case, while it is increased for *City Direct*. The corresponding energy system cost is however increased in both cases, here one needs to remember the objective of the optimisation model. It is not to reduce the charging cost of the buses, but the cost of the energy system.

Table 3.6: Differences between a case with BSRR and a case without (With *BSRR* - Without *BSRR*). Both *City Smart* and the *City Direct* cases are represented. Units are changed compared to Table 3.4 to highlight the changes.

Parameter	Unit	City Smart	City Direct
Storage capacity of stationary batteries	MWh	0.13	2.05
Installed solar PV	MW	-1.02	0.42
Installed total CHP	MW	0.03	0.03
Solar PV electricity generation	MWh/year	-779.35	580.81
CHP electricity generation	MWh/year	373.38	-60.48
Import	MWh/year	171.90	-268.25
Energy system cost	kEUR	4.00	5.00
Cost of charging buses	kEUR/year	-11.25	38.58

The effect of *BSRR* on the energy system for the *City Smart* modelling case is illustrated in Figure 3.15. The power reserve of the electricity system and *BSRR* with and without the requirement enabled in modelling are shown in panel a) and b) respectively. Note the logarithmic scale on the y-axis.

The power reserve of the electricity systems is virtually identical, except for the hours during which the *BSRR* would be violated. In panel a) the system reserve never goes below the reserve requirement of the buses, whereas panel b) illustrates the frequency of violations without the requirement enabled in modelling. The frequency of violations is higher during the winter than in the summer.

Panel c) illustrates the difference in spinning reserve between the case with *BSRR* and the case without. The changes are limited to around twenty events, primarily during winter season. This indicates that for most of the year, spinning reserve is not the primary choice of the model to meet the power reserve requirements.

The difference in SoC of the system's stationary batteries with and without *BSRR* is illustrated in panel d). The dispatch of the batteries is changed during a lot of hours, indicating that the system primarily uses stationary batteries to fulfil the requirement on reserve power.

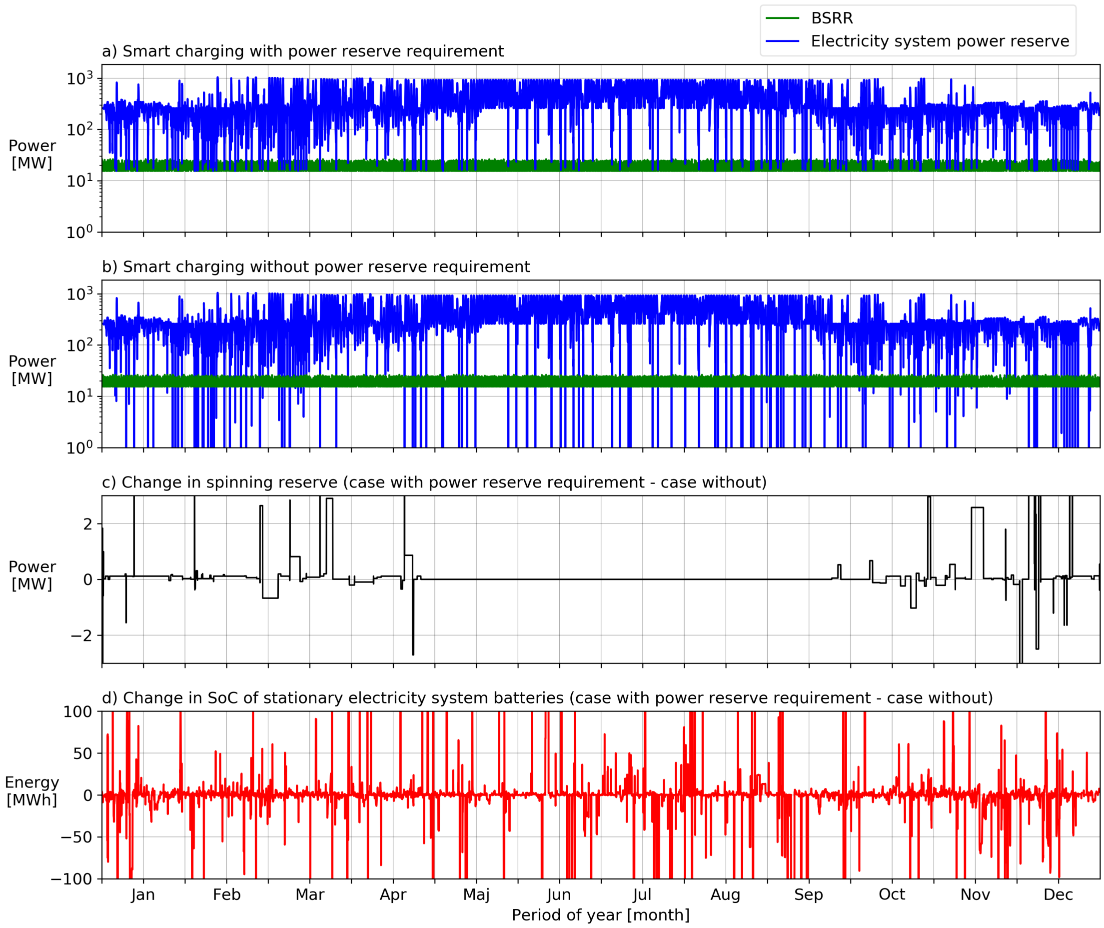

Figure 3.15: The effect of *BSRR* on the energy system for the *City Smart* case. Power reserve of the electricity system and *BSRR* are illustrated with and without the reserve requirement fulfilled. Changes in spinning reserve and SoC are presented.

Figure 3.16 shows an excerpt of panels a), b) and d) of Figure 3.15, covering August 16 to August 26, 2050. As in Figure 3.15, panels a) and b) illustrate the power reserve of the electricity system and *BSRR* with and without the requirement enabled in modelling. Panel a) shows that the *BSRR* is fulfilled during all hours of the period. The *BSRR* is changed in panel a) at e.g. hour 90 which indicates that the model deemed it cost-beneficial to change the charging of buses, compared to panel b), to facilitate fulfilling the reserve requirement. Potential violations are visible in panel b), in which the model did not attempt to change the system's power reserve to accommodate the *BSRR*.

However, most potential violations are prevented by changes in the dispatch of the stationary batteries, as illustrated by panel c). The changes in dispatch of the stationary batteries due to the *BSRR* indicate that a portion of the energy is stored in the batteries is allocated toward fulfilling the reserve requirement. The energy system ensures that this additional energy can be stored by increasing the investment in them, which is reflected in Table 3.6.

The observed increase in the *City Direct* case of 2.05 MWh converted to six minutes of constant power corresponds to approximately 20.5 MW. Which is close to the *City Direct* case's constant reserve requirement of 22.5 MW.

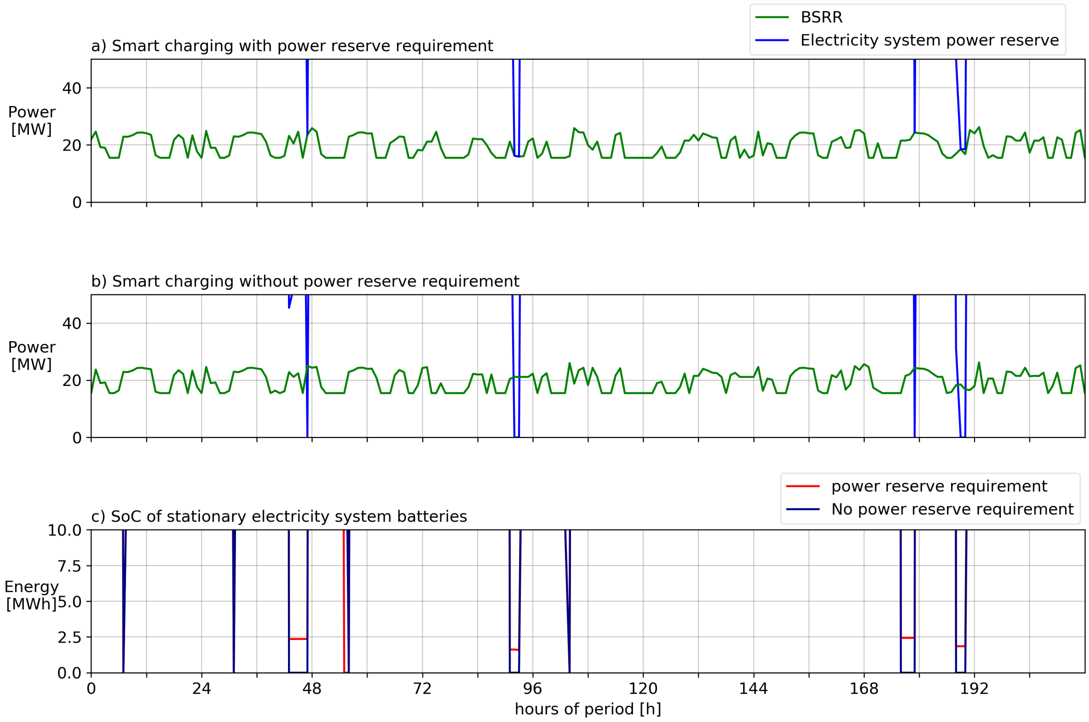

Figure 3.16: Excerpt of Figure 3.15, covering August 16 to August 26, 2050. Power reserve of the electricity system and *BSRR* are illustrated with (a) and without (b) the reserve requirement fulfilled, together with changes in the dispatch of stationary batteries (c).

4

Discussions

This chapter aims to discuss the results and methodology of this work in three parts. The *interpretation of results* discusses the findings and highlights considerations for the electrification of public bus transport in cities. *Limitations in modelling* discusses the shortcomings of the method and what prevents drawing further conclusions from the results. *Uncertainties in development* are presented and their potential impacts on the results in this paper is discussed.

4.1 Interpretation of results

The impact of electric buses on the electricity system is small, suggesting that certain simplifications could be made when modelling electric buses. The charging of BEBs could be cost-minimised using only an electricity cost curve instead of modelling the entire city energy system. This would enable improved optimisation of the buses charging operations since simplifications can be avoided (aggregation and hourly time resolution). For instance, the difference seen between the smart charging in the city and bus scale model largely stems from using the hourly timescale necessitated by the electricity system model. Should the impact of smart charging buses on the electricity system be of interest, it could still be studied by incorporating the cost-minimised charging profile in the electricity system model.

The electricity demand of BEBs overlaps with electricity generation from solar PV, which is reflected in the average electricity mix charged to the buses. Smart charging moves a portion of the load to noon which overlaps with PV generation, further increasing the share of electricity stemming from solar PV. This overlap can be used as an argument to support investments in solar PV in cities, facilitating local electricity generation and increasing self-sufficiency of cities. It is also an argument for the environmental performance of electric buses with regard to the CO_2-emission reduction targets. The use of opportunity charging leads to frequent, short charging events during the day, which can be utilised to steer charging toward desirable time periods.

Electrified public bus transport benefits from diverse charging infrastructure. A bus network can operate with either depot charging or opportunity charging as the main charging technology but operates best with both technologies. Opportunity charging enables charging during the window of operation, whereas depot chargers provide an economically preferable option for slow charging during the time the buses are not in operation. In a configuration with both, charging is possible during all hours of the day greatly increasing the potential of smart charging. This facilitates cost reductions for the PTOs and aids the electricity system by offering flexibility in demand.

Reductions in charging cost are achievable with smart charging, but the impact on total bus ownership costs need to be evaluated. The findings indicate that a charging strategy aiming to minimise energy system cost also reduces charging cost for the PTOs. However, research on the total cost of ownership of battery electric buses indicates that the energy/charging costs are negligible in comparison to driver and vehicle cost [12,13]. It is therefore unlikely that PTOs will adapt charging strategies that benefit the city energy system based on these cost reductions alone.

The larger cost reduction when smart charging in the bus scale model stems from higher flexibility in optimising the charging compared to the city scale model. The city scale reduces charging costs of trunk buses by 7.4 %, whereas the bus scale achieves a 13.5 % reduction. The marginal electricity cost in the city is not affected to a meaningful degree by the buses and therefore not responsible for the difference in cost. The higher flexibility in charging of the bus scale model is reflected in the buses load profile, which is changed to a larger extent than that of the city scale when smart charging is employed.

Rapid variations in the electricity demand of BEBs, caused by high-powered chargers, do not necessarily pose a problem for the energy system. In the studied system, the variations in electricity demand are easily accommodated by a small investment in stationary batteries. Additionally, these batteries are used to facilitate increased solar PV generation during the hours that they are not used as a power reserve.

4.2 Limitations in modelling

The potential of smart charging is limited by assumptions in the bus network creation. The procedure used in this work for assigning buses to trips results in a city bus network that is comprised of too many buses. Including city buses in smart charging would therefore increase the potential flexibility of the system as city buses make up half of the total electricity demand. In reality, these buses offer the same or greater smart charging capabilities compared to the trunk buses, as the driving demand of each city bus route is lower than that of trunk buses. Accounting for the smart charging capability of city buses could reduce the cost of charging further and increase the amount of solar power charged to the buses. Due to the potential for increased charging by solar PV during noon, the electricity demand during the afternoon peak on weekdays could likely be reduced as well. The timetables suggest that driving demand is reduced during the summer period, primarily for the peak buses. This reduction in demand would result in increased flexibility of the buses during this period, however seasonal variation in demand was not considered in this thesis.

The total electricity consumption for electric buses is underestimated by approximately 5 % due to lack of depot travel consumption of city buses. The electricity demand from depot travel is added in post processing according to the buses' category. Due to the aforementioned limitations with creating the city bus network, city buses are not categorised, and no depot trip consumption addition determined. For the trunk buses, the addition contributed around 10 % to the total electricity demand. As the city buses constitute half of the total electricity demand, the 10 % increase in trunk buses can be approximated to be the same for city buses. The effect of the neglected depot travel is an underestimation of the total electricity consumption by 5 %. The depot consumption of city buses could be approximated to occur at the same time as the trunk buses, due to their driving demand profile being similar. The consumption could therefore have been added as a normalised curve of the depot addition from the trunk buses on the city buses.

Variation in electricity demand due to varying auxiliary load in the buses is not considered. The electricity consumption of auxiliary devices on all buses is assumed to be constant over the entire year. This is done to resemble a worst-case scenario and because the seasonal variations of the auxiliary demand are not known. However, a seasonal dependence in the electricity consumption is indicated in the validation data for route 16EL. It is likely to be caused by variation in auxiliary load due to different heating and cooling demand.

The choice of charging system for creation of the bus network is expected to have a large impact on the results. The bus network in this work is created with only opportunity chargers. However, a bus network can be created with only overnight depot charging as well. The depot charging bus network would necessitate the use of more buses and buses with larger batteries, as the battery capacity needs to be sized to cover an entire day of driving operation. This new network would create a different load curve that featured no electricity demand during peak operation hours since no buses are at the depot. If implemented in the city energy system model, the buses would probably have increased flexibility to delay charging due to larger aggregated battery size, but less potential to steer charging towards different hours of the day as the period for charging is smaller.

The method used to ensure sufficient power reserve in the energy system of the city contains an error, causing the reserve to be larger than necessary. The reserve requirement was set to be two times that of all installed opportunity chargers of the trunk buses (22.5 MW). However, the portion of that capacity that is in use during the same time was not considered. This meant that the electricity system at times had both a load of 11 MW satisfied by actual generation and a power requirement of 22.5 MW. This adds up to a required load of 33.5 MW when the load supposed to be required at that time would be 15 MW (11 MW plus the maximum deviation between minute load and hour load curve, 4 MW). The fault resulted in an overestimation of the reserve requirement by around the double amount.

Spatial distribution of transmission capacity and charging infrastructure within the city are not considered in the city energy model. Localised bottlenecks in transmission capacity could increase the difficulty of covering the variations in electricity demand, especially if charging infrastructure is placed in such a location. Detailed information on local transmission grids is typically classified and therefore difficult to consider in modelling approaches. The placement of charging infrastructure therefore needs to be determined with electricity grid considerations in mind[1].

4.3 Uncertainties in development

The timetables of bus routes in use today are based on the driving operation of buses with internal combustion engines but the timetables could be changed with the introduction of electric buses. The PTOs determine the timetable with cost reduction in mind, which can lead to a different result if cost considerations of electric buses are different. It could consider the mandatory breaks for the bus drivers[2], such as to charge longer times during the driver breaks. This cost-minimising optimisation of driver time could then impact the smart charging potential for the electric buses.

The investigated city energy system features a high share of solar PV generation, but the energy system composition of cities could look completely different in the future. The high share of solar PV in the studied city system stems from constraints on CO_2-emissions, a limitation on electricity import capacity from the national grid and the exclusion of certain generation technologies due to space constraints in the city environment. Should the import capacity not be a limiting factor, the city energy system could be less reliant on domestic generation of electricity and be more similar to today's electricity system without the high generation from solar. However, the future national electricity system would probably include more varying renewables, primarily from wind power, which would result in a more varying electricity price than today's system. The smart charging of buses would be impacted by lower solar generation, which results in less charging during noon. The charging will therefore likely be conducted during the night and morning instead of the noon, due to the lack of significant solar PV generation reducing prices during the midday.

There are numerous pathways for the future development of electric buses, and it is not yet clear which design will turn out to be dominant. Improvements in battery technology will affect both technological and economic aspects of buses, leading to different bus network designs. The use of hydrogen as an energy carrier in combination with fuel cells is also discussed in the electric bus context. All these solutions will impact the electricity system in its own way and the difference in their impact is large. This work focuses only on an opportunity charging strategy, since it is the alternative currently suggested for electrified bus transport.

[1] For the interested, an overview of the spatial distribution of fast chargers from our bus network of Gothenburg is illustrated in Figure B.2.

[2] A collective labour agreement regulates the bus drivers' operating time in route traffic. A bus driver requires at least an uninterrupted 10 minutes brake after each 2.5 hours of driving. [14]

5

Conclusion

The primary aim of this work is to create electricity load profiles for the electrified bus network of Gothenburg, Sweden. It is shown that a direct charging strategy of electric buses leads to an electricity demand that correlates with that of the city. During weekdays, buses generate peaks in electricity demand of approximately 15 MW, occurring in the morning and evening. Charging activity is reduced on weekends by 4 MW, removing the two peaks compared to the weekdays.

Smart charging retains the overall pattern in electricity demand, but with increased charging activity during periods of low marginal costs of electricity in the city energy system. It is also evident that the low-cost hours arise from high solar PV generation. Even though charging cannot be avoided during high-cost periods of more than a few hours, smart charging resulted in reductions of charging cost in all tested cases. The reduction in charging cost corresponds to 4.1 % in the city model and 13.5 % in the bus scale model.

Optimisation of a bus network that uses opportunity charging infrastructure can be improved by using a temporal resolution of a minute. The typical duration of charging events of such a system is only a few minutes. Therefore, it is not possible to optimise the charging events of buses using a model with a temporal resolution of e.g. an hour without the loss of information arising from temporal aggregation. An improved model, for studying the effects of smart charging buses on the electricity system in the context of this work, would be to integrate the city model with the bus scale model.

The potential to time charging is predictably limited by the battery capacity of buses and charging infrastructure, but driving demand is also shown to be a deciding factor. The driving demand determines the usage and consequently availability of buses to time charging. The categorisation of buses revealed that buses with low driving demand have a notably increased potential to time charging events. The possibility to time the charging using the high-powered chargers further reduces the impact electric buses have on the electricity system.

Electric buses have no substantial impact on the electricity system and will act as reactive consumers when smart charging. The use of high-powered chargers causes intra-hourly variations in bus charging load of several MW. These variations in electricity demand can successfully be accommodated by small investments in stationary batteries, should sufficient reserve capacity not be available elsewhere. The increase in electricity demand of the city from electrification of buses is to a large part satisfied by additional generation from solar PV.

Bibliography

[1] European Commission: *A Roadmap for moving to a competitive low carbon economy in 2050.* COM(2011) 112 final, 34(March):1–34, 2011, ISSN 1086-1718. https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2011:0112:FIN:EN:PDF.

[2] City of Gothenburg: *Climate Programme for Gothenburg*, 2014. https://goteborg.se/wps/wcm/connect/7ba2b573-9216-4bb9-8a1f-0915b40ce4b5/Climate+program+f%C3%B6r+Gothenburg.pdf?MOD=AJPERES.

[3] Lundström, Anna Cecilia, Matilda Ninasdotter Holmström, Erik Torstensson, and Matilda Eriksson: *Elbussar i Sveriges kollektivtrafik - En kartläggning av Trafikförvaltningen Stockholm, Skånetrafiken och Västtrafik utifrån fyra perspektiv TRV 2018/18530.* Technical report, Trafikverket, 2019.

[4] ABB, Göteborg Energi, Sweco, Vattenfall, Volvo AB, and Volvo Cars: *Projekt PussEl - Vad behövs för att elektrifiera transportsystemet i Göteborg?* Technical report, IVL, 2018. https://www.goteborgenergi.se/DxF-44408010/PussEl___Vad_behovs_for_att_elektrifiera_transportsystemet_i_Goteborg.pdf?TS=636661163438750312.

[5] Svenska Kraftnät: *En statusuppdatering om läget i Kraftsystemet: Systemutvecklingsplan 2020–2029*, 2019.

[6] Heinisch, Verena, Lisa Göransson, Mikael Odenberger, and Filip Johnsson: *Interconnection of the electricity and heating sectors to support the energy transition in cities.* International Journal of Sustainable Energy Planning and Management, 24, 2019.

[7] Östling, Johan, Anders Grauers, Gunnar Ohlin, and Niklas Carlsson: *Energy transfer solutions for electrified bus systems.* Technical report, RISE, 2018.

[8] Västtrafik: *Linjekarta spårvagnar och stombussar*, 2019. https://www.vasttrafik.se/globalassets/media/kartor/linjenatskartor/sparvagn/linjenatskarta-sparvagn-stombuss-190816.pdf.

[9] Larsson, David and ANTON PERSSON: *Shift to electrification.* Master's thesis, Chalmers, 2018.

[10] https://www.electricitygoteborg.se/.

[11] Fastighetskontoret i Göteborgs Stad: *Avtal för förvärv och överlåtelse av mark för bussdepå inom detaljplan för Stadsutveckling vid Järnbrottsmotet inom stadsdelen Järnbrott*, 2018. http://www5.goteborg.se/prod/intraservice/namndhandlingar/samrumportal.nsf/93ec9160f537fa30c12572aa004b6c1a/2c61833977604378c1258308003dd9dc/FILE/19_FN180924.pdf.

[12] Nurhadi, Lisiana, Sven Borén, and Henrik Ny: *A sensitivity analysis of total cost of ownership for electric public bus transport systems in swedish medium sized cities.* Transportation Research Procedia, 3:818–827, 2014.

[13] Olsson, Oscar, Anders Grauers, and Stefan Pettersson: *Method to analyze cost effectiveness of different electric bus systems.* In *29th World Electric Vehicle Symposium and Exhibition (EVS 2016), June 19-22, 2016, Montreal, Canada*, pages 604–615, 2016.

[14] Kollektivavtalstolkning(blabla): *Lawtext*, 2017. https://lagen.nu/dom/ad/2017:5.

[15] *Speedometer 55 pro. gps kit.* https://apps.apple.com/us/app/speedometer-55-pro-gps-kit/id530829008.

[16] Guzzella, L and A Amstutz: *The QSS toolbox manual.* Institut für Mess- und Regeltechnik, Eidgenössische Technische Hochschule Zürich. Zürich, 2005.

[17] Sinhuber, Philipp, Werner Rohlfs, and Dirk Uwe Sauer: *Study on power and energy demand for sizing the energy storage systems for electrified local public transport buses.* In *2012 IEEE Vehicle Power and Propulsion Conference*, pages 315–320. IEEE, 2012.

A

Validation

A.1 Validation of EAEB

The EAEB tool has previously been evaluated by RISE, which found the modelled energy consumption to agree with actual consumption of bus 55. However, since no report of the validation has been published, an own validation is conducted.

A.1.1 Validation with other theoretical approaches

The first validation consisted of choosing a bus line in the tool and analysing it with "back of the envelope" calculations. The calculations consisted of the same energy balance that were used in EAEB, Equation 2.1. The same distance, elevation change and time were extracted from EAEB. The efficiencies were also set the same.

Further validation of the tool featured GPS data collected from bus line 55 in Gothenburg. This data was collected through the app "Speedometer 55 Pro GPS kit" [15], riding the bus one round trip. The extracted data contained: time, distance, velocity and elevation. Vehicle acceleration and road inclination angle were calculated and the data translated into a driving cycle. The energy consumption of the bus was determined in Simulink with the QSS toolbox [16], using the gps-made driving cycle. Efficiency losses of the powertrain components and battery were neglected, and the energy consumption of auxiliaries added as a separate parameter. The vehicle's power requirement at the wheels, P_{wheel} depends on: the drag force, F_{drag}, rolling resistance, F_{rolling}, climbing resistance, F_{climbing} and acceleration force, $F_{\text{acceleration}}$ acting on the vehicle as seen in Equations A.1 to A.5.

$$F_{\text{drag}} = \frac{1}{2}\,\rho_{\text{air}}\,C_d\,A_{\text{frontal}}\,v^2 \tag{A.1}$$

$$F_{\text{rolling}} = C_r\,m\,g \tag{A.2}$$

$$F_{\text{climbing}} = m\,g\,sin(\alpha) \tag{A.3}$$

$$F_{\text{acceleration}} = m\,a \tag{A.4}$$

$$P_{\text{wheel}} = (F_{\text{drag}} + F_{\text{rolling}} + F_{\text{climbing}} + F_{\text{acceleration}})\,v \tag{A.5}$$

where

Table A.1: Vehicle parameters used in the Simulink validation of bus line 55. Values adopted from [17].

Symbol	Value	Variable
ρ_{air}	$1.225\,\mathrm{kg\,m^{-1}}$	density of air
C_d	0.66	vehicle drag coefficient
A_{frontal}	$8.8\,\mathrm{m^2}$	vehicle frontal area
v	varies with time	vehicle velocity
C_r	0.015	rolling resistance coefficient
m	19 000 kg	vehicle mass
g	$9.81\,\mathrm{m\,s^{-2}}$	gravitational acceleration of earth
$sin(\alpha)$	varies with time	road grade
a	varies with time	vehicle acceleration

A.1.2 Validation with empirical data

Ideally, validation of theoretical results should be done with empirical data. The model data is compared to empirical charging sessions data of bus line 16EL. The data ranging from summer 2018 to January 2020 consisted of delivered energy, charging duration and SoC at beginning and end of the session. Delivered energy excludes charging losses occurring in the charging equipment. Charging took place at an opportunity charger at each turnaround stop. Analysis of the data revealed multiple inconsistencies that impeded processing. Therefore, it was not possible to easily extract data for each trip and instead an average energy consumption for the round trip was determined. Additionally, the data was filtered so that any unrepresentative data is excluded. This "selective average" is used for comparison with the theoretical results.

A.2 Validation results of EAEB

The results and the setup of each calculation method were compiled into two tables, Table A.2 and A.3. The two tables represents the two directions of one round trip route. In Table A.2, note that the distance differs between measured distance and EAEB, due to EAEBs discreet use of beeline between stops. Also note that Simulink calculates the consumption with no powertrain and battery losses, whereas EAEB has fixed consumption with a regeneration efficiency of 72 %.

Table A.2: Validation of EAEB with "back of the envelope" calculations and Simulink. Trip: Teknikgatan - Sven Hultin

Model	distance [m]	Δh [m]	Aux [kW]	ΔE [kWh]	$\Delta E/S$ [kWh/km]
EAEB	5861[1]	45[1]	10	15.1	2.60
Back of envelope	5861[1]	45[1]	10	12.9	2.20
Back of envelope	5861[1]	45[1]	0	8.7	1.48
Simulink no regen	7543	49	0	14.8[2]	1.96[2]
Simulink full regen	7543	49	0	9.6[2]	1.28[2]
Simulink no regen	7543	49	10	18.6[2]	2.47[2]
Simulink full regen	7543	49	10	13.5[2]	1.79[2]

[1] according to bee line
[2] no powertrain losses

In Table A.3 one can see that the Simulink value without regeneration contains the highest specific consumption.

Table A.3: Validation of EAEB with "back of the envelope" calculations and Simulink. Trip: Sven Hultin - Teknikgatan

Model	distance [m]	Δh [m]	Aux [kW]	ΔE [kWh]	$\Delta E/S$ [kWh/km]
EAEB	5861	-45	10	10.4	1.77
Back of envelope	5861	-45	10	10.8	1.85
Back of envelope	5861	-45	0	6.7	1.14
Simulink no regen	7703	-45.6	0	11.1	1.44
Simulink full regen	7703	-45.6	0	5.2	0.68
Simulink no regen	7703	-45.6	10	15.7	2.03
Simulink full regen	7703	-45.6	10	9.8	1.27

Table A.4 illustrates the results of the validation. The empirical data represents an average consumption of the two routes(Sahl-Eriks & Eriks - Sahl) of the 16EL line. In this data no charging efficiency is considered since the empirical data is extracted between the charger and the bus and not before the charger. The auxiliary power consumption is unknown for the empirical data and therefore denoted with a "?" in Table A.4. Worth noting is that the charging power ranged from 100 to 200 kW, compared to the 450 kW used in EAEB. It should also be noted that the distance used for the empirical data was determined with Google Maps, and not measured by GPS as the for line 55. In this case due to CoVid-19.

From Table A.4 one can see that the energy consumption per trip, ΔE, is slightly higher in EAEB than that of the empirical data. There is also a clear distinction between seasons in the empirical data. Variations between summer (May, June, August) and winter (November, December, January) months are observed, but cannot be explained with certainty. Probably the difference is caused by the heating system using more energy (it is typically the largest auxiliary and one of the largest energy loads in a bus). The heating system is often complemented with a bio-fueled heater for the coldest days, but this would not impact the observed electric energy consumption.

Table A.4: Validation of EAEB with "back of the envelope" calculations and Empirical data. Trip: 16EL - average of both routes

Model	distance [m]	h-gain/h-loss [m]	Aux [kW]	ΔE [kWh]	$\Delta E/S$ [kWh/km]
EAEB	8197	27/61	10	24.9	3.03
Back of envelope	8197	27/61	10	20.7	2.52
Back of envelope	8197	27/61	0	16.2	1.97
Empirical data winter	10000	37/69	?	21.9	2.17
Empirical data summer	10000	37/69	?	18.1	1.79

EAEB uses beeline distance, which results in an underestimation of the driving distance.

The specific consumption determined by EAEB is slightly higher than that determined by back of the envelope calculations and theoretical modelling with Simulink. In total, the energy use per trip is comparable since the driving distance and specific consumption differences equal out. The same is true when validating with empirical data. Generally, the largest uncertainty is suspected to arise from differences in auxiliary loads.

B

Appendix B

Table B.1: All the bus lines included in the trunk and city model

Trunk buses		
16	19	52
17	25	60
18	50	
City buses		
22	47	82
23	55	83
24	57	84
26	58	86
27	59	90
31	62	91
32	71	92
35	73	93
36	74	94
37	75	95
39	76	97
40	77	99
45	78	

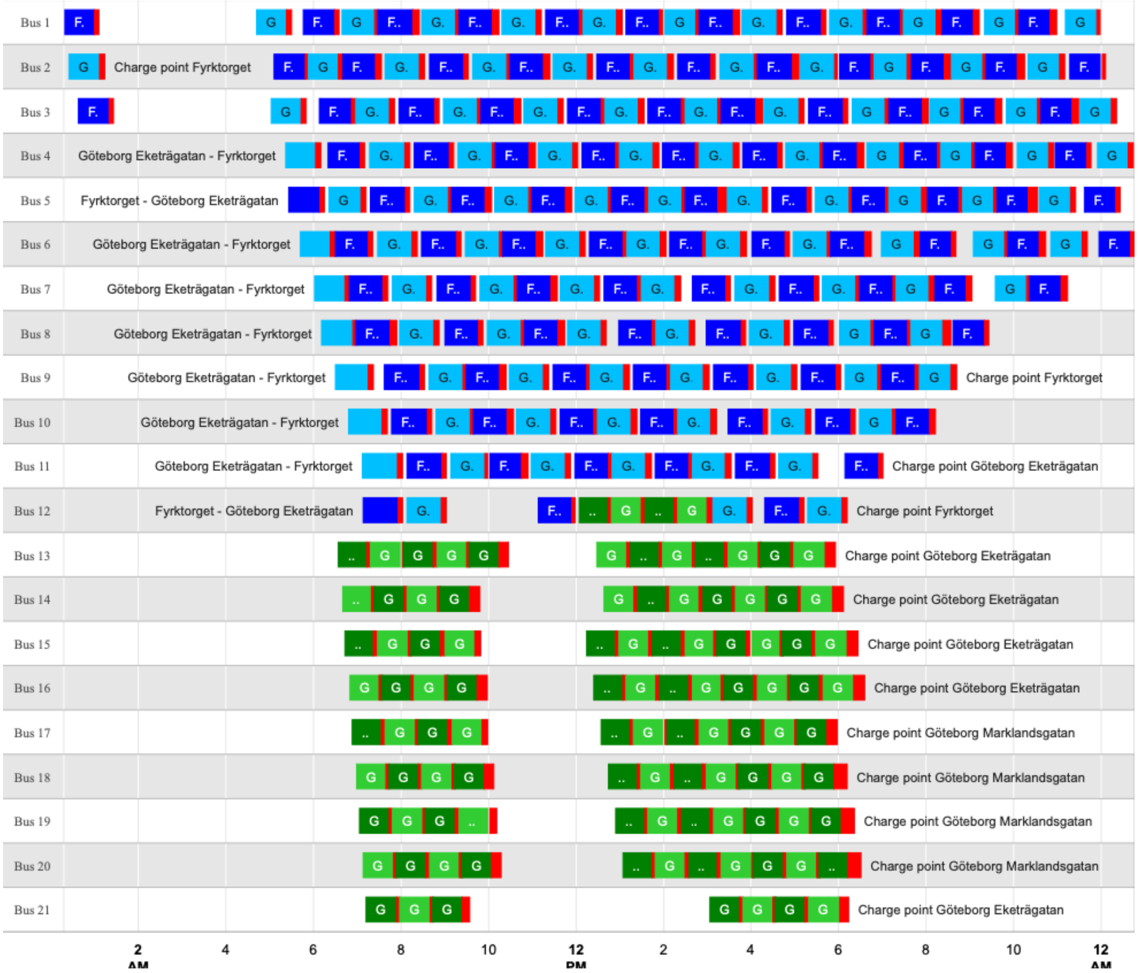

Figure B.1: All assigned buses for route 16 for a weekday.

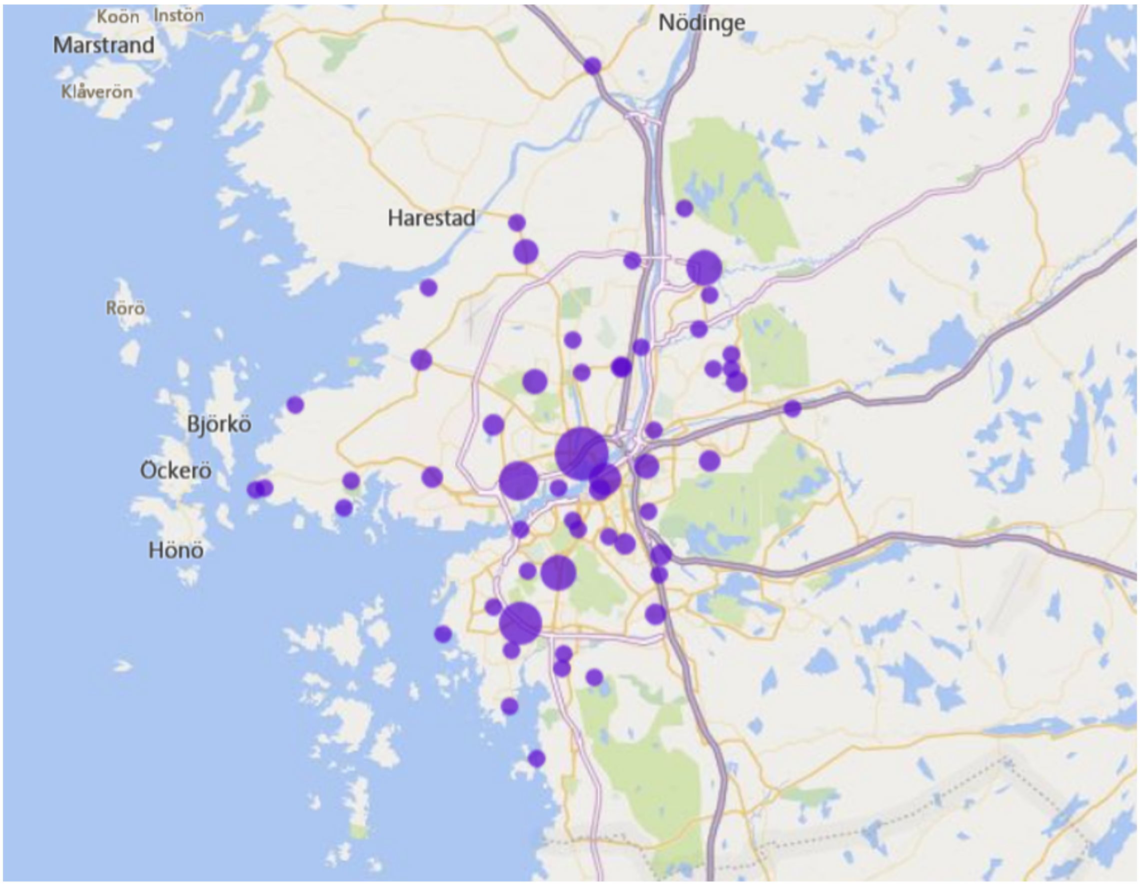

Figure B.2: The spacial distribution of chargers. The circles represents an end stop with a charger, where its size of the circle is equivalent to the number of chargers at this end stop. For reference, the largest circle contains 11 chargers and the smallest 1 charger. The figure is created by the authors on the background of a *Bing Map*.