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TURKU AMK
TURKU UNIVERSITY OF APPLIED SCIENCES

Procurement and commissioning of electric city buses in Turku

Observations from the eFÖLI project 2015–2018

254
Reports

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Contents

Terms and abbreviations **4**

1 Executive summary **5**

2 Background **12**

3 The procurement process **14**
3.1 Tendering process 14
3.2 Technological solutions and requirements of the tender 18
3.3 Data acquisition / analysis 21

4 Observations from the first operative years **23**
4.1 Realized driving output 24
4.2 The charging process 28
4.3 Real-world consumption results 30
4.4 Fuel heater consumption 35
4.5 Specific system-level energy consumption 37
4.6 Energy consumption by vehicle, route segment and the time of day 38
4.7 Effect of driving habits and energy consumption differences between drivers 42
4.8 External circumstances affecting consumption 45
4.9 Charging station consumption measurements 50
4.10 Chassis dynamometer consumption measurements 53
4.11 Total Cost of Ownership 56
4.12 Environmental impact 59

5 Conclusions and discussion **65**

References **68**

Terms and abbreviations

TCO Total Cost of Ownership
HVO Hydrotreated vegetable oil
SOC State of Charge
CCS Combined Charging System
CAN Controller Area Network
TuKL Turun Kaupunkiliikenne LTD
WTW Well-To-Wheel
GVW Gross Vehicle Weight
GHG Greenhouse Gas
CAN Controller Area Network

1 Executive summary

During the years 2015–2017, the City of Turku procured a fleet of six fully electric Link-ker city buses along with two opportunity charging stations, as well as depot slow charging infrastructure. The six e-buses were delivered and commissioned between October 2016 – June 2017, after which the full e-bus fleet has been operational. Operating on the city's bus route number 1 (Harbor – Marketplace – Airport), some 660 000 km had been driven exclusively on the electric buses as of August 2018.

During the tendering process, a weighted scoring system was used to compare the quotations received from the three participants: Linkker Oy, VDL Bus & Coach BV and Volvo Finland Ab. Eventually, Linkker Oy, a Finnish startup company, came out as the winner of the tendering, largely due to receiving a higher score in the "maintenance costs" category for the e-buses and charging systems, respectively, in comparison to the competitors. According to the tendering documentation, Linkker's responsibility was to deliver a turnkey solution of a fully functional e-bus system complete with a fast charging infrastructure. In doing this, Linkker has used subcontractors, most importantly Heliox and Schunk responsible for the charging systems and the roof-mounted pantograph system, respectively.

The complete e-bus system, with all the buses and both fast-charge stations delivered and commissioned, was several months late from the initially agreed schedule, and hence the system was not launched into full-scale production until June 2017. In the first operative years, there have been various planned and unplanned interruptions in the trafficking. The daily kilometer goal of a particular vehicle is dependent on the rotation scheme that the vehicle has been assigned to, ranging between 280 and 340 km. Over the whole pilot project's lifecycle, the daily mileage success rate, measured as the pro-portion of days when at least 275 km were driven on a single vehicle, has been approximately in the range of 70–80%, depending on the vehicle (See Figure 1).

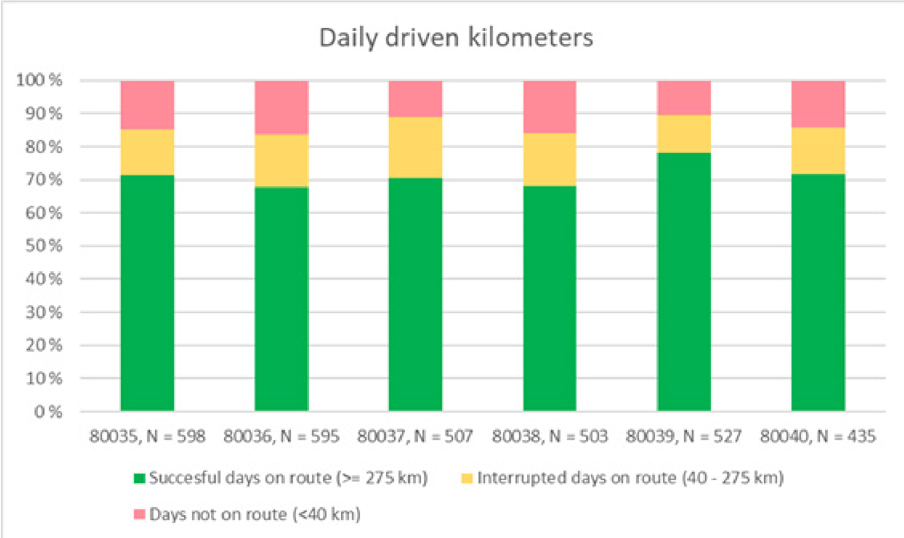

Figure 1. Classification of days according to kilometers driven by vehicle from October 2016 – November 2018

While some improvement has taken place with time, the results obtained during the project remain inconclusive whether a satisfactory level of operation has been reached permanently. In particular, there is a distinct decline in the number of successful days during the winter period 2017–2018 (Figure 2). During the time of writing the report (autumn 2018), the past couple of months have been very good in terms of e-bus mileage. What remained undetermined is if the problems potentially associated with the winter period have been completely resolved and the achieved good performance level can be sustained throughout the cold period of the year.

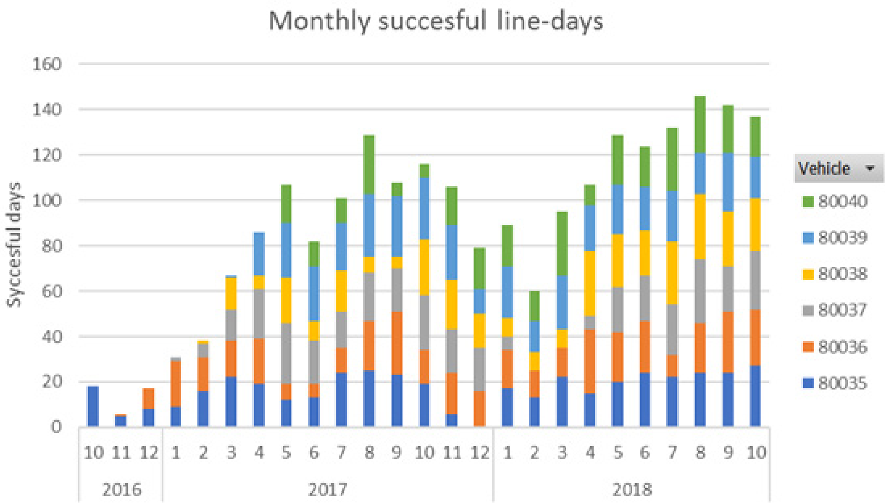

Figure 2. Classification of days according to kilometers driven, aggregation by month and vehicle

The Turku e-bus fleet operates on an opportunity charging scheme, which means that the bus batteries are subjected to frequent high-power short-duration charging events during normal operation. The two fast charging stations are located at the end-of-line stops of the route being trafficked: Turku harbor and Turku airport. The charging takes place at a peak power of 300 kW (measured from the bus side). In practical operation, the active charging durations have been in the order of three minutes (median duration). In addition, the charging process incorporates a so-called dead time, during which the charger is prepared and released. Based on the operational data recorded during the pilot project, this brings an additional overhead of approximately one minute to the total charging duration. The charging process itself is highly automated. In principle, no ac-tion from the driver is required aside from correctly positioning the vehicle in relation to the overhead pantograph and initiating the charging sequence by push of a button from the dashboard.

In terms of energy consumption, the buses have operated satisfactorily. At time of writing, one of the buses have been tested at a standardized chassis dynamometer meas-urement at VTT Technical Research Centre of Finland. In the dynamometer test, the Linkker 13LE e-bus measured in at 0.825 kWh / km in the Braunschweig Cycle at 3000 kg payload. Meanwhile, real-world measurement results from the

Turku route 1 suggest a mean consumption of 0.83–0.95 kWh / km depending on the vehicle, averaging to 0.89 kWh / km across the vehicles.

The energy consumption of the e-buses is observed to vary due to various external cir-cumstances. For instance, we compare daily aggregated values of energy consumption to the ambient temperature, obtaining a correlation with an R2 score of 0.61 between the variables. However, when the data is aggregated more densely, counting each individual trip as an observation of its own, the correlation is significantly weaker with R2 = 0.21. This highlights the notion that on a long enough averaging window, ambient temperature is an important predictor of the consumption, but on the short term, other factors become predominant. As we will illustrate, the short-term consumption is heavily interconnected with e.g. the actual elevation characteristics of the terrain being driven, traffic congestion (peak / off-peak times) and it even varies between individual vehicles.

On a separate note, we also consider the relationship between the driver's actions and the consumption. In an anonymized experimental setup, data collection of the driving habits of 127 unique drivers was conducted. Based on the results, we observe a difference of approximately 25–50% in energy consumption between the most and the least energy efficient drivers. While this kind of variation is not uncommon in the case of traditional diesel buses either, it is arguable that some of the engineering aspects particular to a fully electric bus – mainly the regenerative braking property – further enhance the driver's role in economical driving.

The consumption measured from the buses is not the same as the system-level energy consumption. Rather, as we will illustrate, the losses involved in the operation of the charging infrastructure have, on average, increased the total energy consumption by approximately 21 percent during the observation period. Converted to specific consumption this averages to an overhead of 0.19 kWh / km. This statistic is based on comparing the data collected directly from the e-buses' CAN bus with information derived from the bus operator's (Turun kaupunkiliikenne Ltd) accounting books. Further-more, we remark that the total efficiency of the system is greatly dependent on the utilization rate of the charging infrastructure due to the fixed energy costs involved.

The buses still consume a specific amount of diesel fuel because of the integrated auxiliary fuel heater. During a one-year observation period, we compute the fuel heater's consumption to be approximately 3.2 liters / 100 km averaged over all the vehicles. This corresponds[1] to additional energy overhead of 0.32 kWh / km. Hence, summarizing the different consumption components, we end up with a system-level specific consumption estimate of:

$$E_{system} = E_{operation} + E_{charginglosses} + E_{fuelheater}$$

$$E_{system} = (0.89 + 0.19 + 0.32\ )\ {}^{kWh}/_{km} \approx 1.4\ {}^{kWh}/_{km}$$

For comparison, the specific consumption of traditional EURO5 diesel buses are known to be in a distinctly higher range. For instance, VTT's LIPASTO-coefficients[2] suggest average diesel fuel consumption of approximately 42 liters / 100 km for a EURO5 class diesel bus with a 50% payload, operating on typical Finnish urban driving cycle. Subsequently[1] a quick specific consumption estimate of 4.2 kWh / km representative of urban city bus traffic in Finland is obtained for diesel-operated buses. Thus, the e-bus system as a whole, counting all the losses and consumption components seems to be competitive in terms of energy efficiency.

In this study, we present a baseline scenario TCO metric of 0.85 € / km for operating the e-bus fleet, according to Lankila (2017). This result is in good agreement with other recent literature where modern opportunity charging e-bus systems are analyzed, most importantly Pihlatie et al. (2015) and Lehtinen & Kanerva (2017). The TCO will greatly vary if operative parameters such as the yearly mileage and system lifetime deviate from the baseline scenario. Altogether, if operating goes as has been planned, this indicator suggests a competitive edge for e-bus systems from a financial standpoint, too.

Finally, we assess the e-buses' potential to reduce the carbon footprint of urban city traffic and improve the cities' quality of air. As of August 2018, some 500–800 tons of CO_{2eqv} emissions (tank-to-wheel) were avoided in the City of Turku thanks to introduc-tion of the e-buses, not counting emissions from the fuel heater. Emissions that are directly harmful to humans, such as nitric oxides, are also significantly mi-

1. *Using 10 kWh / liter as heat of combustion for diesel fuel*

2. *Calculation system developed by VTT Technical Research Centre of Finland for estimating transport emissions and energy consumption in Finland, based on large international databases and experimental findings*

tigated compared to diesel buses. A well-to-wheel analysis conducted suggests that the Linkker BEV, operated on an average Finnish electricity mix, has a significantly lower carbon footprint than the fossil diesel counterpart (Figure 3). The superiority between fully electric and renewable diesel (HVO) operated buses is not quite as clear due to high variability of HVO's emission characteristics as a function of the feedstock, production method and calculation methodology.

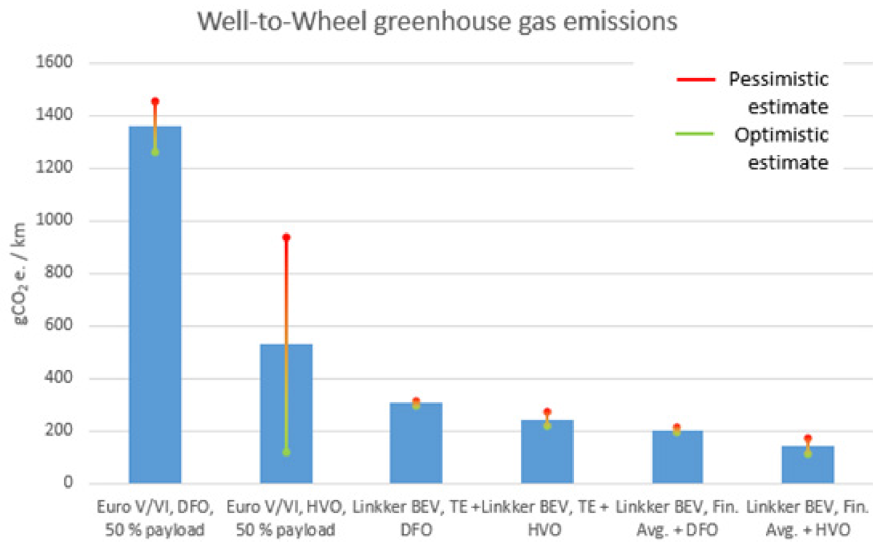

Figure 3. Well-to-Wheel analysis of various fuels of transportation. Linkker values include the operation of fuel heater.

We conclude the analysis by summarizing the experiences and important findings to be taken in to account when planning any future e-bus tendering, specifically in Finland or other Nordic countries with similar challenges. In future projects, the learning curve needs to be steeper, in the sense that it must be possible to introduce e-buses on currently operational routes with minimal disturbance to the operations. During the pilot project, some important lessons have been learned, including but not limited to:

- From a technological standpoint, the core components of the electrical drivetrain and battery systems of the vehicle have, during the project, functioned satisfactorily

- From an energy efficiency point of view, the system has proved its competitiveness against traditional diesel bus operations

- Problems have occurred with some of the most critical auxiliary devices. For instance, the importance of reliable HVAC system cannot be stressed enough in northern conditions, since it is a matter of passenger comfort and, perhaps even more importantly, driver's working conditions

- For the general acceptance of e-buses, PR management is of utmost importance. When an e-bus is being maintained or serviced for whatever reason, the general public will blame this on the new technology, even if the root cause is trivial in nature (e.g. problem with an auxiliary such as interior infotainment screen)

- Failures will happen from time to time – sufficient number of spare vehicles needs to be readily on hand to be deployed on route should the need arise

- The system components need to be dimensioned with sufficient redundancy, so that there is a reasonable overhead to overcome slight distractions, such as a fast charging station malfunctioning. On the other hand, having a margin too wide will hurt profitability; hence, a tradeoff exists between TCO unit cost and reliability.

- The overall efficiency and hence profitability is highly dependent on the utilization rate of the fixed charging infrastructure – a matter which constitutes an optimization problem of its own in the scale-up phase of e-bus systems

This report highlights some of the most important aspects of introducing a modern opportunity charging e-bus system to operational urban mass transit system. It is the author's hope that the documented progress in Turku may help other cities as well with their endeavors towards electrification of public transportation and, in this, provides useful insights to be used by decision makers, industry and scholars alike.

2 Background

Turku region traffic Föli produces public transportation services for the municipalities of Turku, Kaarina, Raisio, Naantali, Lieto and Rusko in Southwest Finland. The renewed joint operation between the six municipalities has been in action since 1 July 2014, after which unified ticket products, fees etc. have been applicable throughout the region. Year 2015 was Föli's first full operational year, during which 24.4 million public transport trips were recorded in total. Föli procures the majority of the traffic from private contractors, and additionally Turun Kaupunkiliikenne Ltd, a subsidiary owned 100% by the City of Turku, operates some of the routes. (Föli 2014, 2015)

In 2009, WSP Finland Ltd has produced a thorough report examining the different possibilities for the development of Turku's regional public transportation. In the report, two alternative main courses of action are proposed. In particular, constructing a new light rail system or investing in a high-capacity bus route network are considered. (WSP 2009) In autumn 2009, a decision was made by the city council to move forward with the plans of implementing a high-capacity bus network. (Turun kaupunginvaltuusto 2009).

The city council has decided on 8 October 2013 that the City of Turku will take an active role in promoting the use of electric and biogas operated vehicles, both on the city's own and the city's service providers' operations. In terms of public transportation, it was decided that in future vehicle procurements the city would gradually increase the proportion of fully electric and electric-diesel hybrid buses in the public transport fleet. Hybrid buses have been in operation since 2011 on Turku bus routes 3 and 30.

In 2014, a M. Sc. thesis was commissioned by the City of Turku from Tampere Technical University, in which the possibilities to commission fully electric buses (e-bus) were examined. In the thesis, the routes showing most potential for electrification were identified, namely routes 1, 3, 30, 4, 40 and 18. These routes were thoroughly analyzed in terms of technical feasibility, economical sustainability and regional development. (Lehtinen 2014)

On 1 June 2015 the city council approved the starting of an electric bus pilot project on route 1. This particular route was found to be a pivotal backbone route in Turku's internal traffic, and hence an attractive target to showcase the new technological developments. Moreover, it was determined that the route was a feasibly sized entity in terms of the effectiveness of the pilot project as well as risk management factors. (Turun kaupungin-hallitus 2015)

Up until 30 September 2016, Föli had an ongoing traffic contract with LS-Liikennelinjat Ltd. At the time of starting the electric bus procurement, a decision was made to transfer the traffic to Turun Kaupunkiliikenne Ltd, a direct subsidiary of the city. This is reasoned with the technological and operative risks associated with the experimental nature of the project, when only limited experience exists in operating an electric bus fleet in the varying northern conditions. As it was found, dealing directly with a subsidiary company instead of a market-driven vendor would bring some flexibility in to negotiating different aspects of operational, financial and technical characteristics of the project. (Turku City Board 2015)

3 The procurement process

3.1 Tendering process

The actual procurement process began in autumn 2015. In the procurement, a restricted process was used. In September 2015, a public request was issued for companies to express their interest towards participating in the tendering. At this stage, companies were also allowed to request additional information about the tendering. Eventually, the companies Volvo Finland Ab, VDL Bus & Coach BV, Solaris Bus & Coach S.A, Linkker Oy, BYD Europa B.V. and ABB Oy issued notifications of participation. On 9 November 2015, a decision was made about the companies to be included in the final tendering phase, which were Linkker Oy, VDL Bus & Coach BV and Volvo Finland Ab. A request for quotation (RFQ) was then published on 26 November 2015, and revised multiple times. (City of Turku 2016)

According to the RFQ, the target of procurement has been "six (6) new fully electric bus-es and one (1) charging system including two (2) fast charging stations and one (1) slow charging station". Moreover, a prerequisite for the vendors has been to commit to maintenance contracts for the aforementioned systems. In essence, a turnkey solution has been requested in the RFQ: "The electric buses and charging systems are procured as a ready-to-use entity, installed to the locations notified in the RFQ" (City of Turku 2016). The RFQ in itself is a 35-page document, consisting of e.g. technical requirements, notes about delivery and commissioning, and conditions regarding the maintenance of systems to be procured. (City of Turku 2016)

Appended to the RFQ, the participants have received information about the target to be trafficked, which is the Turku city's bus route number 1 operating on the route Turku harbor – central market – Turku airport. Among other relevant data, a general description of the traffic and the planned vehicle rotation scheme has been delivered to the participants. Moreover, the planning documentation and illustrations (See Figure 4 for example) of the airport's and harbor's fast charging stations have been provided. Finally, an on-site event was hosted by the City of Turku at the installation sites in order for the participants to even better familiarize themselves with the planned installations and ask any further questions from the relevant experts. (City of Turku 2016)

Figure 4. An illustration of the fast charging installation at the Turku harbor, an excerpt from the RFQ documentation provided to the participants in tendering

Furthermore, as a part of the RFQ, the participants have received a velocity graph from route 1 as measured by Turku University of Applied Sciences. Figure 5 illustrates the data provided, but in conjunction with the actual RFQ the data were also provided in a tabulated csv format. The aim was that this information, along with appropriate heuristic estimates about e.g. passenger load and other factors, would enable manufacturers to better evaluate the energy consumption in real-world operation of the line. This, in turn, could provide useful insights to engineering decisions, such as dimensioning the bus batteries and other powertrain components. In general, the idea has been to be as open as possible in providing information about the target of trafficking, in order to receive tenders of highest possible quality.

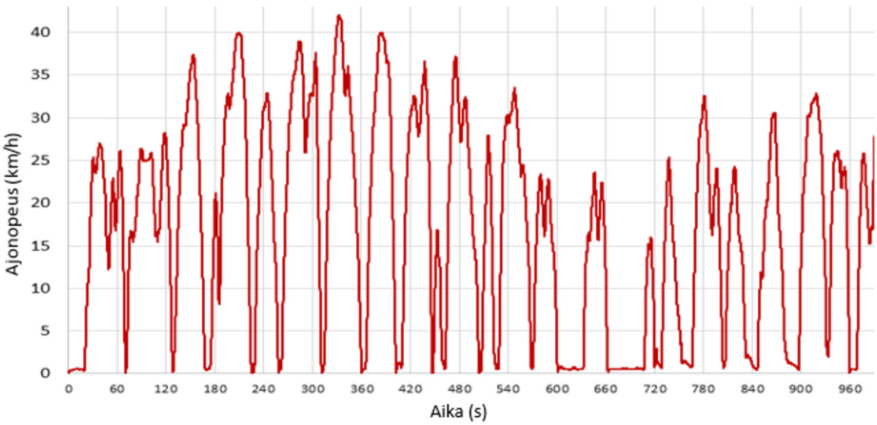

Figure 5. An excerpt of the velocity graph representative of bus operation on route 1 (Turun Kaupunki 2016)

All three companies selected to tendering submitted a quotation before the deadline 22 January 2016. Evaluation of the tenders took place by a weighted scoring system, which was disclosed to the participants beforehand. The largest weights were assigned to the electric buses' and charging systems' price. Other criteria were involved e.g. with the maintenance services and the approximated energy consumption of the buses. The comparison of the quotations and scoring has taken place on 5 February 2016, the results of which are displayed in Table 1. The winning tenderer was Linkker Ltd, a Finnish startup company. (City of Turku 2016)

Table 1. Summary of the tender comparison criteria and scoring of the quotations.

Vertailun pisteytys	Painoarvo	VDL Bus & Coach bv	Linkker Oy	Volvo Finland Ab
Sähkölinja-autojen hinta	50	45,471	47,619	50,000
Sähkölinja-autojen huolenpitosopimuksen hinta	30	1,698	30,000	1,154
Sähkölinja-autojen huollon aukioloaika	10	5,090	5,389	10,000
Sähkölinja-autojen huollon kokoaikaisen sähköteknillisen koulutuksen saaneen huoltohenkilökunnan määrä	10	1,250	5,000	10,000
Sähkölinja-autojen sähköenergian kulutus	10	7,273	10,000	8,000
Sähkölinja-autojen nopeuden rajoitus kauko-ohjatusti	10		10,000	10,000
Sähkölinja-autojen korin pituus	10	0,000	8,000	0,000
Latausjärjestelmän hinta	30	20,339	30,000	20,339
Latausjärjestelmän huolenpitosopimuksen hinta	15	4,463	15,000	4,463
Yhteensä	175	85,583	161,008	113,955

The tendering process can be compared with an electric bus tender done in Tampere in 2015. Notably, both cities have chosen to procure the whole e-bus system as a turnkey delivery from one single contractor, who is allowed to use subcontractors. There are also differences between the cities. For instance, Tampere decided to completely omit the energy consumption of the buses from tender comparison, mainly because the measurement and validation of this property was perceived difficult. (Kotakorpi & Siikasmaa 2016) On the contrary however, in Turku's tendering the participants were explicitly required to disclose their buses' energy consumption in accordance to the standardized Braunschweig-cycle (Dieselnet 2013) in the unit kWh / km. According to the procurement contract, the true energy consumption would be validated post-commissioning on a standardized chassis dynamometer test. Should the vehicle fail to meet the consumption reported in the quotation, financial penalties might incur to the vendor of the vehicle.

The organization of the procurement differs between the cities of Turku and Tampere. In Tampere, the buses and charging systems are directly owned by the city (Kotakorpi & Siikasmaa 2016), while in Turku, the ownership is in the hands of the city's subsidiaries. In particular, Turun Kaupunkiliikenne Ltd owns the buses and Turku Energia Ltd owns the charging stations. In contrast to Tampere, this is a major difference in principle. Specifically, the ownership and responsibility of operating the charging stations is a matter that needs to be resolved at latest when electric buses become more common and private contractors start operations with them. Hence, it is beneficial for the e-bus community to gain experience from various different business models.

In Turku, the period of contract for the maintenance of the delivered electric buses and charging stations is 7 years with a 3-year extension option. For the charging systems, the participants of tendering were asked to offer three alternative levels of service: narrow, extended and wide support, all featuring a different level of financial compensation. In the maintenance contract between Turku Energia and Linkker, the wide support level was initially chosen. Turku Energia can change the level of service by a written notice at any time. When the operations have stabilized, and some experience is gained of the routine maintenance operations, very fast response times for support might no longer be required. In this case switching to a more suitable service scheme might prove to be profitable.

The maintenance contract concerning the buses has been agreed between Turun Kaupunkiliikenne Ltd and Linkker Ltd. According to the contract, planned maintenance is carried out on the vehicles between every 30 000 km driven. Similar to Tampere, maintenance days per year are limited to a certain number, after which penalties can incur to the manufacturer for extraneous days. The contract also mentions separately the replacement costs of the batteries. While, in the normal case, the replacement of worn-out batteries is included in the standard maintenance contract, there is somewhat of a catch involved. According to the contract, the financial responsibility of changing the batteries is reverted to the operating company (Turun Kaupunkiliikenne Ltd) in the case a predetermined driving output (km) is surpassed during the 10-year contract period. Should this scenario realize, the operation could quickly turn very unprofitable from the perspective of the operating company.

The total value of the procurement of Turku's e-buses and charging systems is approximately 3.8 million euros, out of which approx. 1 million euro is awarded as an investment grant by the Finnish Ministry of Economic Affairs and Employment. Moreover, 780 000 EUR has been awarded by TEKES to carry out the eFÖLI e-bus research project in conjunction with the procurement. Concurrently with the eFÖLI project, the City of Turku also aims to become a carbon neutral city by promoting smart mobility in general, including walking, cycling, electric public transport and shared use of vehicles. All of these will be developed in CIVITAS ECCENTRIC, an international EU-funded project that was launched at the beginning of September 2016.

3.2 Technological solutions and requirements of the tender

The delivered system is based on Linkker 13 fully electric buses. The identifier "13" ac-counts to the vehicle's length, with is precisely 12.8 meters according to the technical data sheet provided by the manufacturer (Appendix 1). The vehicle's length has been beneficial for Linkker during the scoring of the quotations, since Linkker's competitors were only offering 12.0-meter buses. Previously the route has been operated by 15-meter bogey buses, but at the time of procurement vehicles of this type were not available as electrical versions from any known manufacturer. Illustrative of an e-bus commissioning project being not only technological, but also operative in nature, the time between departures on the route has been reduced from 20 minutes to 15 minutes. This was done in order to approximately preserve the previous overall passenger capacity of the route.

One particular technical feature which has raised plenty of discussion amongst the Finnish e-bus community is the mounting method of the pantograph used in the fast charging process. The pantograph can be mounted to the bus or the charging station (Figure 6). In Turku, the so-called reversed pantograph (right on Figure 6) was chosen as the fast charging technology. This is contrary to the solutions made in Tampere and the Helsinki area's e-bus systems, where they have opted for the bus-mounted pantographs (left on Figure 6). Overall, this technological diversity is good in the initial phase, since it allows the community to get experience from both solutions' pros and cons. However, it is the author's view that likely one or the other will prevail in the future systems, which also enhances the interoperability of buses and chargers from different manufacturers.

Figure 6. Normal (left) and inverted pantograph (right)

The fast charging process takes place at approximately 300 kW peak power[3], while the battery capacity is 55 kWh, hence giving a theoretical charging time of about 11 minutes from empty to full. According to Linkker's documentation, a single charge gives 30–50 km of operative range, varying on the route characteristics, driver action and other external circumstances (Appendix 1). In Turku, the one-way trip from end-of-line to end-of-line is no more than 13 kilometers. In practical operation, the batteries thus need not be completely depleted, nor charged up to their theoretical maximum (Figure 7). During the first operation year, the median effective fast charging times have been in the order of three minutes (see Figure 13, p. 29). Mathematically, this would correspond to a mean transferred energy of approximately 15 kWh, suggesting that just about a third of the battery's full capacity is in effective use. This

3. *Measured from the vehicle side – the manufacturer reports a charging efficiency of 0.95*

capacity reserve can be thought to increase the immediate investment costs of the system, while it is a good solution in terms of batteries' lifetime; the relationship between the average depth-of-discharge and cycle-life of a battery is well-documented in literature (see e.g. Rahn & Wang 2013, p. 22; Battery University 2018; Xu et al 2016; Väyrynen 2016). Furthermore, the capacity reserve ensures the continuity of operation during various exceptional circumstances, e.g. if the driver cannot charge due to schedule reasons or if one of the fast charging stations has a malfunction preventing charging.

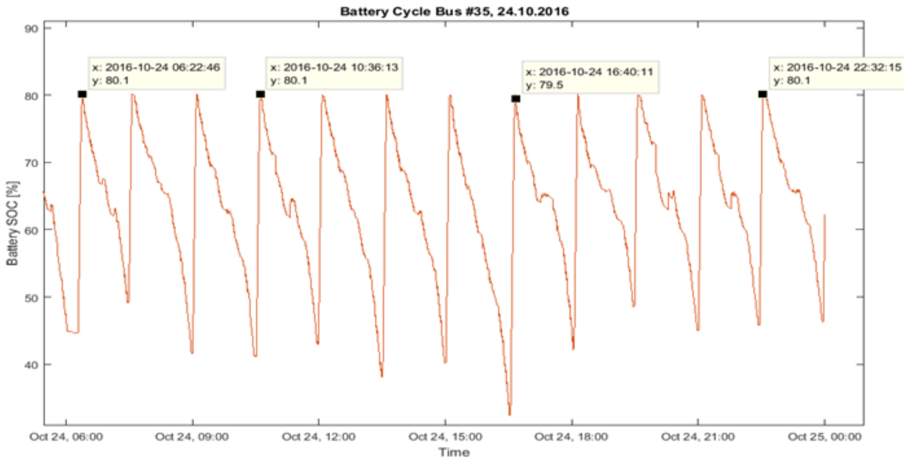

Figure 7. During normal operation, the battery State of Charge (SOC) mostly remains between 40 % - 80 %, which is known to be beneficial for the battery lifetime.

In addition to the fast charging, the buses are charged overnight on the depot. The slow charging power is adjustable between 22–55 kWh. The charging interface is a normal CCS plug that is also present in many electric passenger cars. At the time of the delivery, there was an issue with the placement of the plugs. Contrary to what had been agreed at the time of procurement, the CCS plug was placed at the rear of the bus instead of the front (Figure 8). At the time of the procurement, it was specifically determined that the buses need to be able to be driven to the slow charging front-first. Reversing the bus, possibly in a confided space, can be a challenging task even for an experienced driver. Unnecessary reversing should be eliminated from daily operation, since it inherently incurs additional repair costs because of small collisions with the surroundings. Corrective action was taken once the plug misplacement became apparent, however this is one of the points that should be emphasized in future procurements if slow charging is to be used.

Figure 8. At time of delivery the buses needed to be reversed to slow charging due to placement of the CCS plug. The metal fence visible in the background causes a risk of collision. (Markku Ikonen)

3.3 Data acquisition / analysis

In Turku, the e-bus procurement has been carried out as a part of the TEKES-funded eFÖLI project. In addition to the procurement, the project entity contained the tasks of adapting the route for e-bus operation, definition and procurement of the charging stations, and the creation of the operation model and novel service contracts between the different stakeholders.

As a part of eFÖLI, Turku University of Applied Sciences (TUAS) has carried out a research entity that aims to ensure the actual energy consumption of the buses and, to a lesser extent, develop other methods to extract some interesting insights from the data produced by the buses and charging systems. The aim is to produce key figures and indicators that can be utilized when making any future investment decisions. Moreover, driver training is carried out by TUAS staff in order to study the effectiveness of optimal driving to the overall sustainability of the route in comparison with diesel buses.

The data acquisition from the buses has been realized on IoT Ticket platform, produced by Wapice Ltd. Approx. 200 sensors/channels are constantly monitored and saved to a cloud database. In addition, TUAS has made an agreement with EEE Innovations Ltd concerning the data acquisition directly from the vehicles' CAN bus, in order to get data with an even higher sampling rate, which is required for accurate energy consumption modeling. Anonymized driver identification has also been implemented to the data acquisition, which makes it possible to analyze the consumption and other indicators even according to the driver's behavior. In addition, charging system's data is acquired from a web-interface provided by Liikennevirta.

In addition to data acquisition and analysis, TUAS has participated in training and production of training materials for the drivers, maintenance staff and even personnel of the emergency services. TUAS' staff has also been involved in commissioning and maintenance of the infotainment screens inside the buses. Some of these tasks have been realized as student projects. TUAS' students have also completed multiple bachelor's theses regarding different aspects of the e-bus operation, ranging from total cost of operation analysis (Lankila 2017), developing data acquisition and analysis systems (Wahlsten 2017), energy flow modelling of the e-bus system (Koivisto 2017), and the temperature dependence of the e-bus energy consumption (Taavetinkangas 2018). TUAS representatives have taken part in the national eKEKO forum, which aims to interconnect the key personnel within the e-bus pilot projects in ongoing in different Finnish cities (Turku, Tampere and the Metropolitan region). The aim is to share best practices and provide a forum to exchange experiences about different operational and technological solutions.

4 Observations from the first operative years

The original delivery schedule, taking in to account all the six buses and charging sys-tems, has been delayed several times. The original deadline for delivery, as per agreed in the tendering phase, has been 18 September 2016. The operative responsibility of route 1 was transferred to Turun Kaupunkiliikenne beginning 1 October 2016. Before starting operations, a couple of weeks were scheduled to system testing and driver training. However, already during spring 2016, the delivery schedule was altered in such a manner that two vehicles would be available at the beginning of the operation, that is, 1 October 2016. The remaining four vehicles would be delivered at latest before the end of year 2016. In the meantime, it was agreed that Linkker will supply diesel vehicles as spares in order to start the operative traffic as planned.

The first vehicle was delivered to Turku in mid-September 2016. Before starting actual operation, basic driver training and testing of the airport's fast charging station was con-ducted. The operation started on a single vehicle on 1 October 2016, as was agreed. The second vehicle was a few weeks late, and by the beginning of November, two electric buses were on route in operative use. The third and fourth vehicles were also delivered late, in early 2017. The last vehicle was delivered in May–June 2017. Because also the harbors' fast charging station was commissioned late, on 15 December 2016, it can be summarized the procured entity as a whole was several months late. In addition to the operative difficulties incurred, this inevitably had some consequences in terms of PR, since the commissioning of the e-buses in Turku was widely recognized by local and national media.

Immediately following commissioning, many different flaws and problems were observed in the vehicles and charging systems, due to which the traffic has been periodically halted on some of the vehicles. One large subset of problems has to do with the charging system and how the fast charging can be made as reliable as possible from the driver's perspective. In terms of data analytics, the problems manifest themselves as a large number of prematurely terminated or otherwise unsuccessful charging attempts in the data acquisition system. These problems undermine the effectiveness and reliability of the system and cause additional stress and frustration for the drivers.

The technological root cause of the problem varies. For instance, there have been problems with the placement of an IR sensor and an undersized cooling system of the fast charger. On a separate note, during the course of the operation drivers have repeatedly reported of problems in cabin heating. While the temperature in the passenger space has been quite adequate, the driver's working area has sometimes been unacceptably cold. Measures have been taken by Linkker to remedy the situation, and reportedly, there has been some improvement. Nevertheless, in northern conditions this indeed is something that cannot be stressed enough in future procurements, as it is a vital safety and well-being factor of the drivers.

4.1 Realized driving output

The vehicles are yet to reach their planned yearly km-output. The annual kilometer goal of a particular vehicle is dependent on the rotation scheme that the vehicle has been assigned to. There are in total nine rotation schemes, out of which six are intended for working days (Monday to Saturday) and three for Sundays and midweek holidays. The different rotation schemes are outlined in Table 2.

Table 2. The planned e-bus rotation schemes for route 1. Minimum and maximum daily planned kilometers are highlighted in bold red.

Rotation scheme #	1	2	3	4	5	6	7	8	9
Weekday	Mon - Sat						Sun		
Begin time	5:15	5:30	5:15	5:15	6:15	5:45	6:00	6:15	5:15
Stop time	1:05	22:42	0:22	22:20	0:35	22:07	1:05	0:35	0:22
Hours on route	19:50	17:12	19:07	17:05	18:20	16:22	19:05	18:20	19:07
Km's on route	**341.7**	296.5	327.2	294.6	314.6	**280.2**	325.3	312.7	325.4

Because the actual scheme being driven by a particular vehicle might change from day to day, a precise long-term mileage goal cannot be stated for a single vehicle. Instead, in the following analysis we utilize computational maximum and minimum scenarios based on data described in Table 2. In Figure 9 we depict the cumulative planned and actual kilometers from approximately the first six months of operation of one of the vehicles. In order to conclude that the vehicle would have reached its planned utilization rate, the realized output should run somewhere in between of the minimum and maximum. Characteristic of the actual operation is that vehicles are kept at an operational pace for long periods of time, but there is also a high number of interruption periods. By the naked eye, several periods of traffic interruption (flat regions in the gray graph) can be seen in Figure 9, ranging approximately between 1–4 weeks in duration.

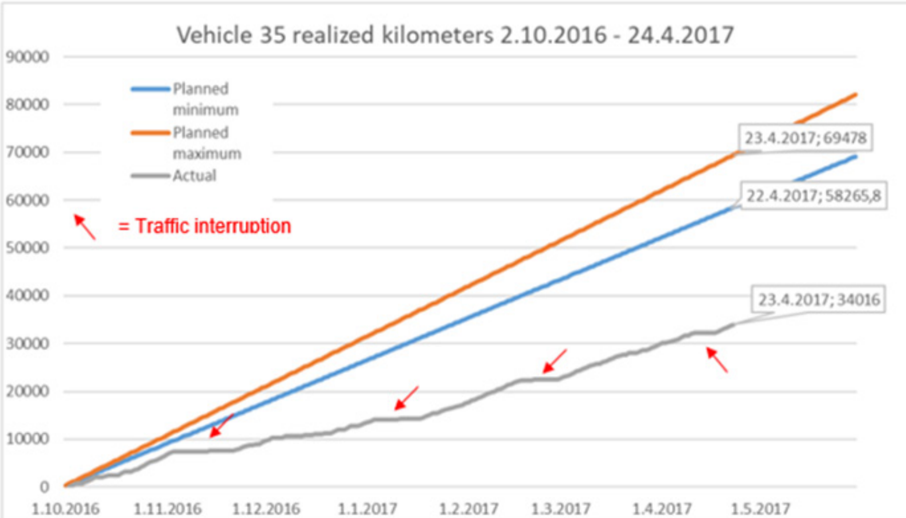

Figure 9. Planned and actual driven kilometers on a single vehicle immediately after commissioning, period Oct. 2017 – Apr. 2017

A single explanatory factor for the anomalies depicted by the red arrows in Figure 9 cannot be stated, but instead there is a multitude of reasons why the traffic has periodically been halted. Although only a rough high-level classification, the reasons could be broken down to following categories:

- Bus auxiliary malfunction or maintenance (e.g. interior screens, fuel heater)
- Charging infrastructure malfunction
- Planned maintenance and service
- Vendor’s planned campaigns (e.g. moving the placement of the CCS plugs)

- Operative reasons (i.e. operator decides not to put the particular bus unit on route, although the bus would be fully functional)

Rather than looking at the cumulative values, though, it is the author's view that it is more useful to discuss the driven kilometers aggregated to daily sums. Figure 10 shows an example of such analysis, where each day's kilometers driven by a single vehicle are plotted along with a 90-day moving average. While the average line does seem to show a general upward trend, the result remains inconclusive whether the target level of operation has been reached permanently. Similar figures from the other vehicles can be found in appendix 2.

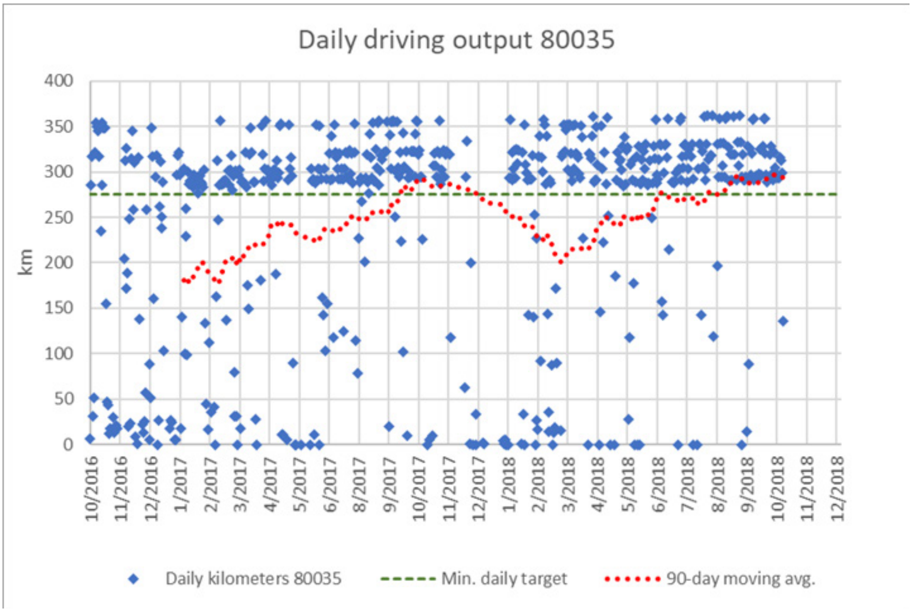

Figure 10. The realized driven kilometers from a single vehicle October 2016 – November 2018

Qualitatively, we classify the operative days to the following categories:

1. Days where driving according to the original route plan (operative distance > 275 km, green line in Figure 10)
2. Interrupted on-route operation (40–275 km)
3. Not on route (< 40 km)

In Table 3 we summarize the classification over the whole pilot project, spanning roughly a 2-year period October 2016 – November 2018. We see the amount of successful days ranging roughly from 70% to 80% between the vehicles, or conversely, roughly 20–30% of the time the vehicles have faced trouble reaching their daily mileage goals. This can be due to technical failure, but equally well an operative decision by the PTO not to drive a particular vehicle on a particular day for other reasons that are beyond the scope of this analysis.

Table 3. Classification of days according to kilometers driven by vehicle from October 2016 – November 2018

	80035	80036	80037	80038	80039	80040
Observed days	598	595	507	503	527	435
Succesful days on route (>= 275 km)	427	403	356	342	412	312
Interrupted days on route (40 - 275 km)	82	94	94	80	59	61
Days not on route (<40 km)	89	98	56	81	56	62
Succesful days on route (%)	71 %	68 %	70 %	68 %	78 %	72 %
Interrupted days on route (%)	14 %	16 %	19 %	16 %	11 %	14 %
Days not on route (%)	15 %	16 %	11 %	16 %	11 %	14 %

The data provided in Table 3 is further visualized in Figure 11.

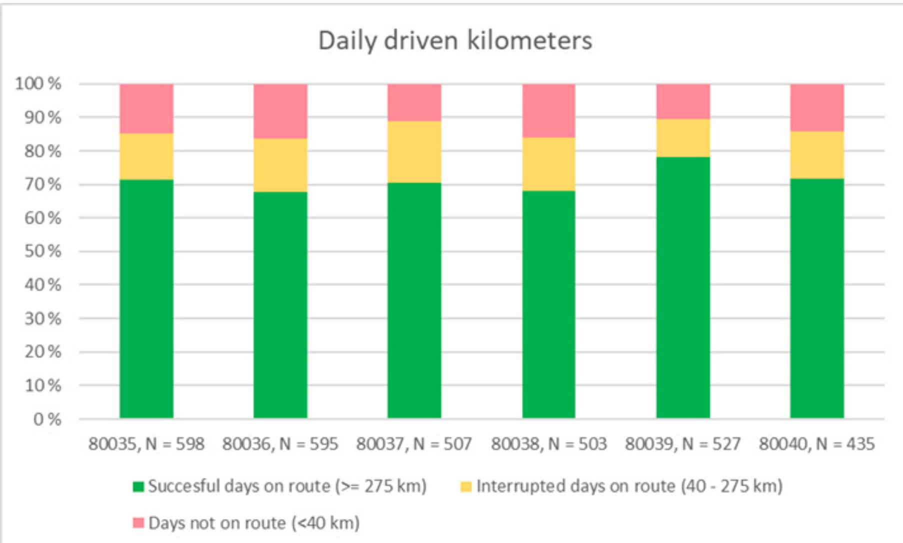

Figure 11. Classification of days according to kilometers driven by vehicle from October 2016 – November 2018

An additional view is obtained by looking the data on a monthly basis, as is done in Fig-ure 12. During time of writing, the three preceding months (Aug.–Oct. 2018) have been record-breaking in the amount of successful days on route. Meanwhile, somewhat worrisomely, there is a considerable decline during the winter period of 2017–2018. It remains to be seen if the problems potentially associated with operation during winter have been resolved and if the good utilization rate achieved now will be preserved even when temperatures start declining again. Careful analysis and monitoring are recommended for the operating companies.

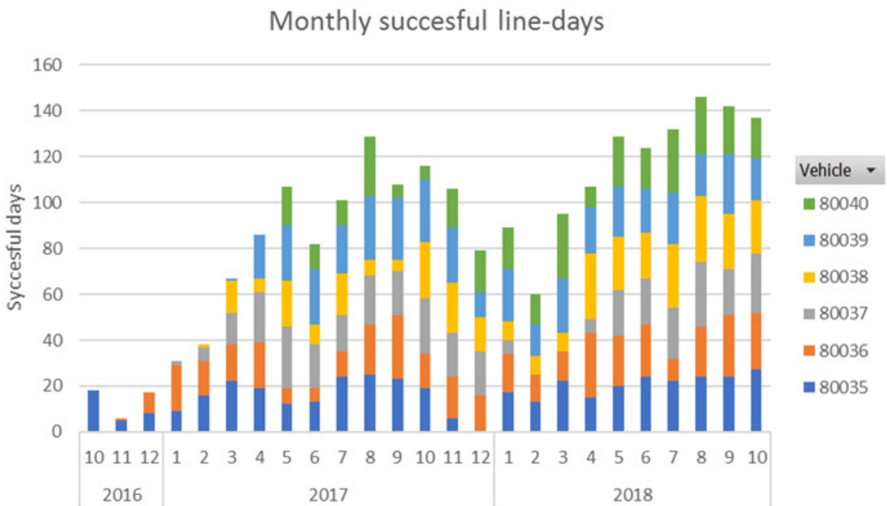

Figure 12. Classification of days according to kilometers driven, aggregation by month and vehicle

4.2 The charging process

The fast charging process is highly automated and, in principle, the driver's only respon-sibility is to correctly position the bus in relation to the overhead pantograph and to initiate the charging process by pressing a button on the vehicle's dashboard. After that, a handshake data transmit sequence takes place, where the pantograph connection is established, and identification takes place between the charging system and the bus to authorize the charging. Correspondingly, after the actual charging has terminated, there is a release phase, where the process is finalized, and the pantograph connection is detached. After this, the vehicle is once again ready for operation.

The time allocated for the charging process is an important engineering constraint when designing any e-bus system. It needs to account for the handshake and release phases – so called “dead time” – in addition to the effective charging time. Optimally, one naturally wants to minimize the proportion of the dead time. In Turku’s e-bus system, the durations of the different phases in the process were analyzed utilizing the diagnostics data obtained from the buses’ CAN bus. The status of the charging system is recorded as a time series consisting of the integers 1 to 8. Status codes 3, 4 and 5 have to do with the handshake phase while 7, 8 and 1 are the release phase. Active charging takes place during status code 6. Status code 2 is a charger standby mode, roughly corresponding to the vehicle being involved in a non-charging activity, such as driving on route, and is hence excluded from the analysis.

When the status codes 1–8 are recorded consecutively, we record a complete charge-discharge cycle. During the period 10/16 – 03/17, in total 2 385 such cycles were recorded, which allows for an analysis of median times of the various phases. Figure 13 outlines the main results.

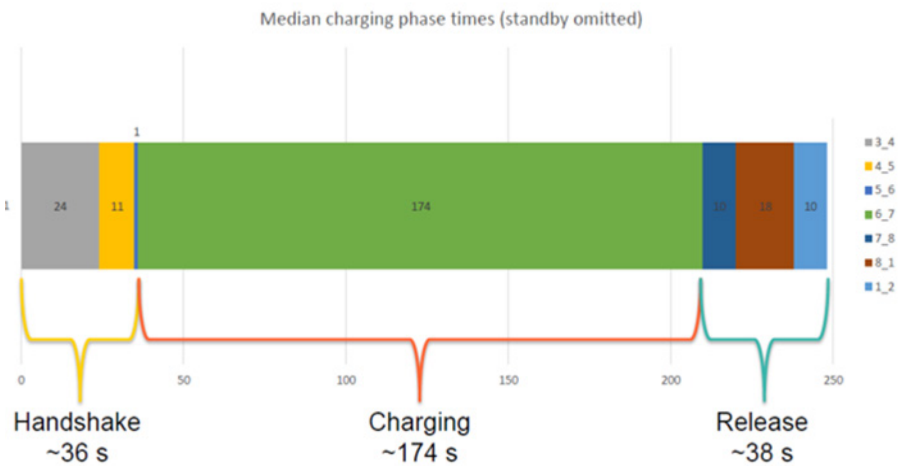

Figure 13. The median durations of the different phases in the fast charging events (N = 2385) as recorded by vehicle 80035 during 10/16 – 03/17

It is observed from Figure 13 that in this example dataset, the effective charging time median has been around three minutes, while the handshake and release time medians are in the range of 30 seconds each. From this, we obtain a rough estimate of the proportion of the dead time in the charging process:

$$\frac{(36+38)\ s}{(36+174+38)\ s} \cdot 100\% \approx 30\%$$

In total, the charging process takes on average close to four minutes. This does not account for the time it takes for the driver to position the vehicle correctly in the charging site. While not a huge issue, this might have some effect on the overall performance of the charging system, particularly for inexperienced drivers.

4.3 Real-world consumption results

Depending on the preferred point of view, various performance indicators and figures can be extracted from the vehicle data. Perhaps the simplest one, and at the same time the most interesting to the operating company, is to simply look at the charged grid energy per kilometer driven, shown in bold at the bottom row of Table 4. Although this indicator only indirectly takes in to account regeneration's relative effect to the total consumption, it is clear that on the long run the regeneration decreases the charging requirement.

Table 4. Consumption data from the vehicles (August 2018)

	80035	**80036**	**80037**	**80038**	**80039**	**80040**
Battery Total External Energy, kWh	116361	116008	92387	91109	109179	81487
Odometer, km	131218	122486	111215	102588	123853	93425
Charger-to-vehicle consumption, kWh / km	**0.89**	**0.95**	**0.83**	**0.89**	**0.88**	**0.87**

Solely relying on the vehicles' information system does not, unfortunately, tell the whole truth about system-level energy consumption. In fact, the total electricity consumption, as invoiced by the energy company from the operator, can in normal operation be 20–25% higher than the consumption reported by the buses' data acquisition. The analysis shown in Table 5 was conducted by aggregating monthly sums of the buses' "Battery Total External Energy" parameter from the period October 2016 – April 2018. The data obtained was then compared against monthly values inferred from TuKL Ltd.'s accounting books, serving as a proxy for the consumed kWh values measured by Turku Energia on-site. Initially, the aggregate bus data contained in total four outlier days, i.e. days where the reported charged energy was unrealistically high, such as 100 000 kWh. The consumption for these days was replaced with the median, 232 kWh, for the whole dataset. Eventually, the results displayed in Table 5 were obtained.

Table 5. External electricity consumption as measured from the vehicle's information system and invoiced from the operator. The system-level consumption is significantly higher than what the vehicles consume alone.

	kWh, invoiced	kWh, measured	Km driven	Invoice / meas	Grid-To-Battery eff.
October 2016	8625	5941	6465	145 %	69 %
November 2016	6470	3656	3457	177 %	57 %
December 2016	12845	9268	8743	139 %	72 %
January 2017	19109	14259	13020	134 %	75 %
February 2017	20373	15832	14522	129 %	78 %
March 2017	31067	25094	24400	124 %	81 %
April 2017	36412	29814	30790	122 %	82 %
May 2017	37504	31282	36017	120 %	83 %
June 2017	29917	25362	30609	118 %	85 %
July 2107	33494	28090	34911	119 %	84 %
August 2017	40211	34206	43259	118 %	85 %
September 2017	35886	30402	37000	118 %	85 %
October 2017	41194	35082	38630	117 %	85 %
November 2017	39587	33819	37198	117 %	85 %
December 2017	33297	27543	29002	121 %	83 %
January 2018	38301	32238	32069	119 %	84 %
February 2018	30400	24871	22562	122 %	82 %
March 2018	39242	32862	32102	119 %	84 %
April 2018	35997	30556	34981	118 %	85 %
TOTAL	**569932**	**470177**	**509737**	**121 %**	**82 %**

The difference between the invoiced energy and the energy measured from the bus batteries is mainly explained by losses taking place in the charging event itself, as well as the idle consumption of the charging system (See Ch. 4.9 for details). Moreover, these results highlight a very important aspect of any e-bus operation – the economy of scale. During the first months, we observe very poor results in overall efficiency, which is explained by the low utilization rate of the whole system. When only one or two buses are in active duty, the relative proportion of the idling losses – the fixed costs - become more prominent, and hence the overall efficiency remains low. After the introduction of more and more buses, getting the kilometers up, we can see the overall Grid – To – Battery efficiency stabilizing to a more acceptable level of 80–85%. Figure 14 provides a visualization of the phenomenon discussed.

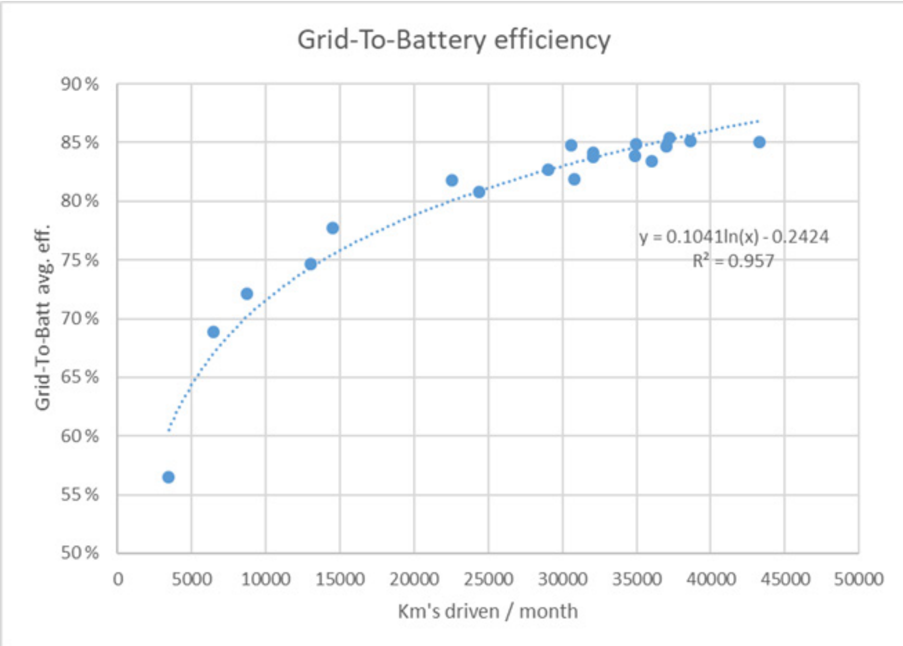

Figure 14. Grid-to-battery average efficiency as a function of monthly kilometers. We provide a logarithmic fit for visualization purposes only.

An additional visualization is provided in Figure 15 which shows the data from Table 5 as a time series, along with checkpoints at times when a new e-bus has been introduced. Again, it is clearly observed that for the system-level efficiency it is beneficial to have as many vehicles utilizing the charging stations as possible.

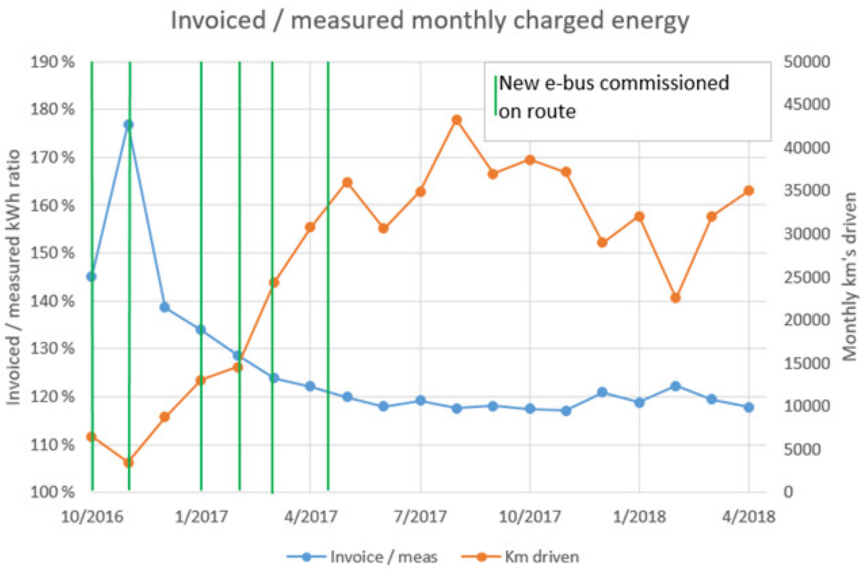

Figure 15. Invoiced and measured monthly charged energy and monthly kilometers

Formally, the relationship between the utilization rate and grid-to-battery efficiency can be modeled as the function eff_{total}:

$$eff_{total}(d) = \frac{e_{sfc} \cdot d}{e_{sfc} \cdot d + \left(1 - eff_{chg}\right) \cdot e_{sfc} \cdot d + E_{idle}}$$

Where

e_{sfc} = the approximate specific consumption of the fleet (kWh/km)

d = total kilometers driven over the observation period (km)

E_{idle} = the idling consumption of charging infra over the observation period (kWh)

eff_{chg} = The approximate charging time efficiency

As it turns out, it can be shown[4] that as d approaches infinity, $eff_{total}(d)$ approaches $1/(2-eff_{chg})$. In other words, the charging-time efficiency imposes an upper limit for how high the grid-to-battery efficiency can be made by increasing the utilization rate

4. *See appendix 4 for mathematical derivation*

(mileage), provided that other parameters remain constant. A visualization is presented in Figure 16, where we show the computed values from Table 5, along with the modelled trajectory of $eff_{total}(d)$. Furthermore, we infer from the model some example points from hypothetical scenarios where optimal mileage is achieved with a varying number of vehicles.

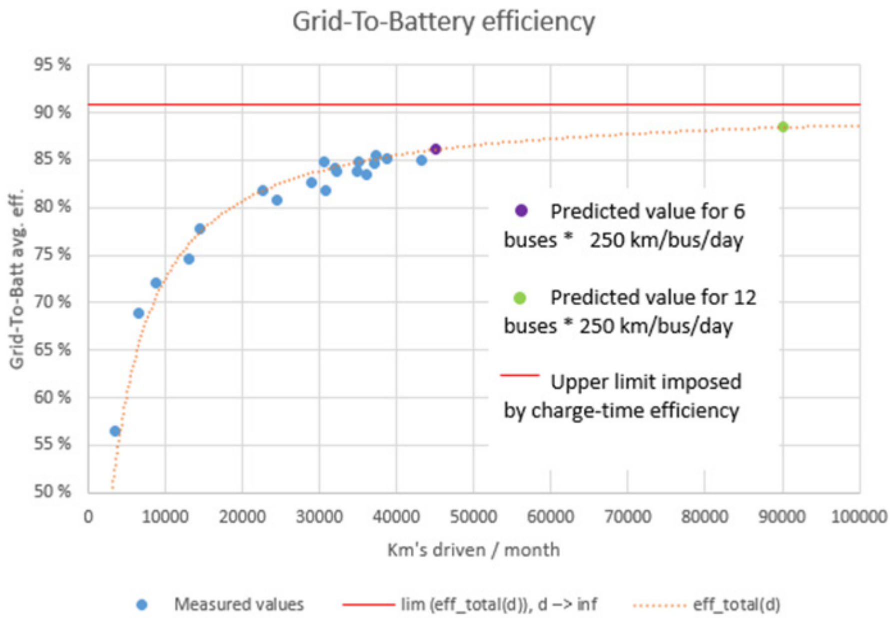

Figure 16. Modelling the grid-to-battery efficiency as a function of monthly driven kilometers with constants: e_{sfc}=0.9 *kWh/km* , eff_{chg}=0.9 , E_{idle}=2500 *kWh.*

Finally, the system level efficiency is greatly dependent on the idle consumption of the charging infrastructure. As it is illustrated in Figure 17, lowering the fixed part of the total energy consumption enables the system to achieve a good overall efficiency level at a lower mileage.

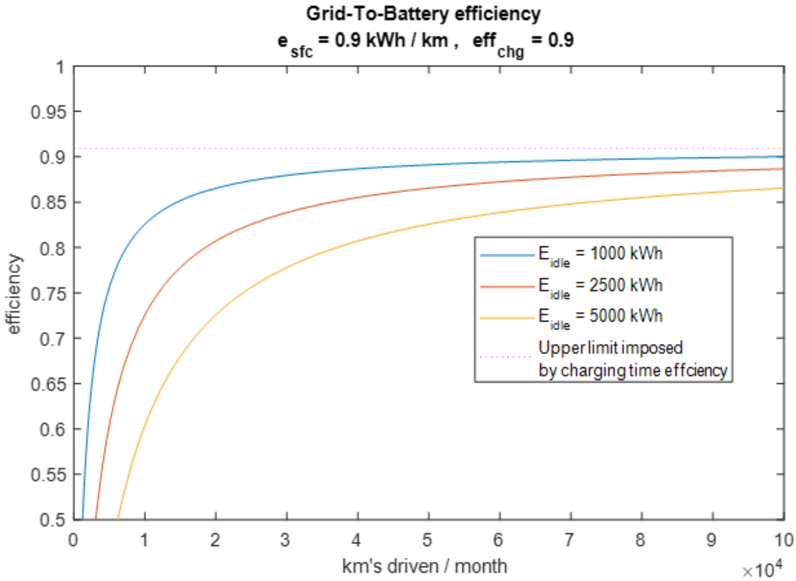

Figure 17. System level efficiency with varying levels of idle consumption.

4.4 Fuel heater consumption

The Linkker e-buses are equipped with a 24-kW diesel operated Eberspächer heater unit, the consumption of which must be taken in to account when determining the total energy usage of the buses. In Figure 18 we present the fuel heater's consumption aggregated by the month, based on refueling journals provided by Turun Kaupunkiliikenne Ltd. In total, the analyzed dataset featured the refueling quantities recorded from the six vehicles on the period March 2017 – April 2018. The original data included some outliers; specifically, on nine separate occasions refueling quantities of over 40 liters were reported, exceeding the maximum capacity of the eberspächers fuel tank. Since these are clearly mistakes in data collection, these instances are excluded from any further analysis.

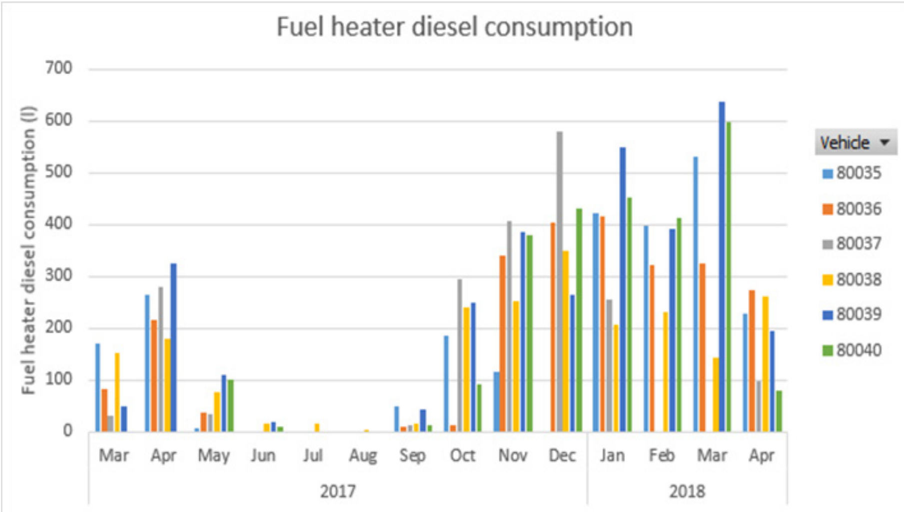

Figure 18. Fuel heater diesel consumption by month and vehicle

Utilizing the vehicles odometer data, we can obtain metrics for the consumption of the Eberspächer. The main results from analysis are presented below in Table 6. It should be noted that considerable uncertainty is associated with estimating the consumption for the individual vehicles from refueling and odometer data alone. Hence, we only present an average figure summarized over all the vehicles, which will also be utilized as a thumb-rule estimate in subsequent energy efficiency computations.

Table 6. Fuel heater diesel consumption. For calculations, we use 10 kWh / l as approximation of diesel's heat of combustion.

	80035	80036	80037	80038	80039	80040	Total
Km's driven	78908	78610	74970	71449	97051	62542	**463530**
Eber refuellings (l)	2373	2445	1993	2148	3226	2567	**14751**
Eber diesel usage (l / km)	N/A	N/A	N/A	N/A	N/A	N/A	**0,03**
Eber energy usage (kWh / km)	N/A	N/A	N/A	N/A	N/A	N/A	**0,32**
Eber usage (l / 100 km)	N/A	N/A	N/A	N/A	N/A	N/A	**3,18**

4.5 Specific system-level energy consumption

We conclude the main part of energy consumption analysis by summarizing the various consumption components presented in Ch. 4.3 and 4.4, that is:

- The electricity consumption caused by operating the vehicle, as measured by the vehicle's data acquisition system, including driving and operation of all electrical auxiliaries

- The overhead electricity consumption of operating the charging stations, as inferred from Turku Energia's on site measurement reduced with the buses' consumption on the equivalent time period

- The fuel heater's energy consumption

The odometer and BTEE values are from period October 2016 – August 2018. For calculating the charging losses, we use the average value of 21% computed from the period October 2016 – April 2018 (Table 5). Finally, the fuel heater's consumption is approximated to be 0.32 kWh / km, as approximated across all vehicles from data obtained in March 2017 – April 2018 (Table 6). The resulting total system-level consumptions are depicted in Table 7.

Table 7. Energy consumption components

	80035	**80036**	**80037**	**80038**	**80039**	**80040**	**TOTAL**
Battery Total External Energy, kWh	116361	116008	92387	91109	109179	81487	**606531**
Charging losses, kWh	24436	24362	19401	19133	22928	17112	**127372**
Fuel heater consumption, kWh	41990	39196	35589	32828	39633	29896	**219131**
Total, kWh	182787	179565	147377	143070	171740	128495	**953034**
Odometer, km	131218	122486	111215	102588	123853	93425	**684785**
Charger-to-vehicle consumption, kWh / km	0.89	0.95	0.83	0.89	0.88	0.87	**0.89**
Charging losses, kWh / km	0.19	0.20	0.17	0.19	0.19	0.18	**0.19**
Fuel heater consumption, kWh / km	0.32	0.32	0.32	0.32	0.32	0.32	**0.32**
System-level consumption kWh / km	**1.39**	**1.47**	**1.33**	**1.39**	**1.39**	**1.38**	**1.39**

It must be remembered that while the charging losses and fuel heater add significant overhead to the system overall consumption, the system remains very competitive against traditional diesel buses in terms of energy efficiency. For instance, VTT's LIPASTO-coefficients[5] suggest average estimated energy consumption of 4.2 kWh / km representative of urban city bus traffic in Finland operated on traditional diesel. This still is approximately three times as high as the total energy consumption estimate from Linkker buses on Turku's route 1, as presented in this work.

4.6 Energy consumption by vehicle, route segment and the time of day

The analyzed data consisted of 25,256 unique trips and was collected from the electric bus traffic in Turku during the year 2017. Due to an error in the data acquisition, only four vehicles' data instead of six was usable, due to an error in registering the remaining two buses' GPS position. The number of the trips by vehicle and route segment is presented in Table 8.

Table 8. Summary of the trip data used in the vehicle-, route segment and driver-based energy consumption analysis

Route segment / vehicle	80035	80037	80038	80040	**TOTAL**
Airport - Marketplace	2203	1860	1344	1241	**6648**
Marketplace - Harbor	1763	1541	1178	978	**5460**
Harbor - Marketplace	1993	1786	1291	1167	**6237**
Marketplace- Airport	2237	1975	1403	1296	**6911**
TOTAL	**8196**	**7162**	**5216**	**4682**	**25256**

In Figure 19 the distribution of the energy consumption over the route segments is pre-sented. The indicator chosen for this analysis is the change in state of charge (Delta SOC) as percentage points, when driving each route segment from start to end point. In terms of consumption, it would seem that the segment between the harbor and market place is equally demanding in both driving directions, since the median is close to 5% Delta SOC in both cases. On the segment airport – market more significant deviations can be observed in the medians, primarily due to proper-

5. *Calculation system developed by VTT Technical Research Centre of Finland for estimating transport emissions and energy consumption in Finland, based on large international databases and experimental findings*

ties of terrain elevation on that particular segment. On a separate note, we observe the distributions to be generally skewed towards the higher values in delta SOC, due to the large number or outliers proposed by the visualization algorithm.

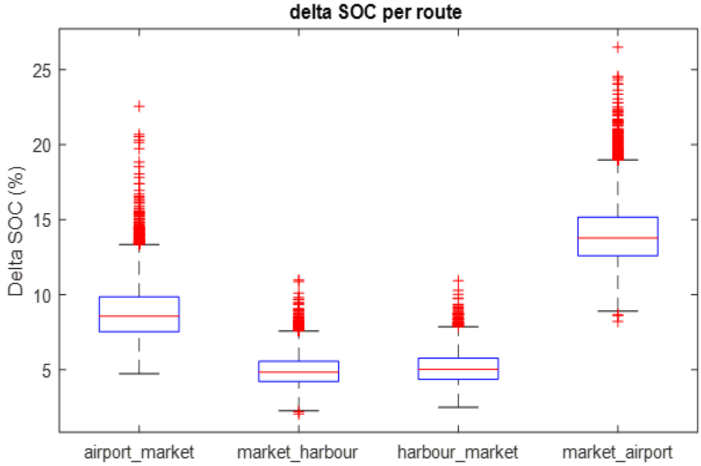

Figure 19. Distribution of energy consumption (Delta SOC) on different route segments

For convenience, in Figure 20 we present the same data approximated as kWh / km, computed from the Delta SOC, the nominal battery capacity of 55 kWh and the length in kilometers of each respective leg.

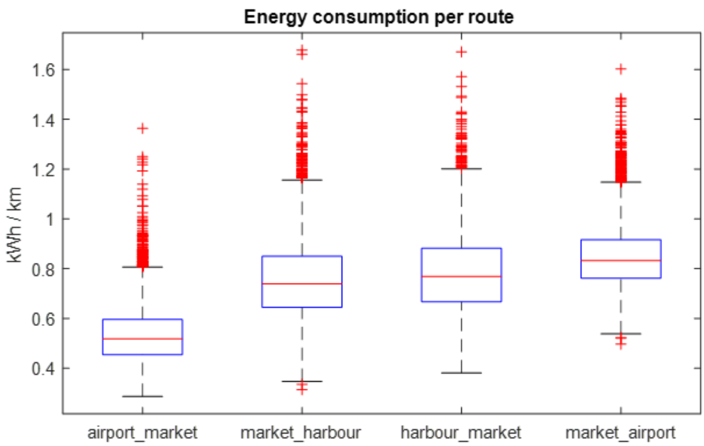

Figure 20. Distribution of energy consumption (kWh / km) approximated from Delta SOC. For illustrative purposes only.

We emphasize that this is merely an approximation, and any scientific or technical use of the approximations given in Figure 20 beyond illustrative purposes is discouraged. This is due to the various nonlinearities existing between the SOC and the actual charge of the battery at a given point in time. Furthermore, since the metrics in Figure 20 are approximated from Delta SOC, they are only representative of the energy *dis*charged from the battery during the driving operation, and not in direct relation to the charged energy as discussed in Ch. 4.3 (p. 30).

In terms of examining different vehicles, attention is drawn to vehicle no. 80038, which seems to slightly surpass the other vehicles in consumption (Figure 21).

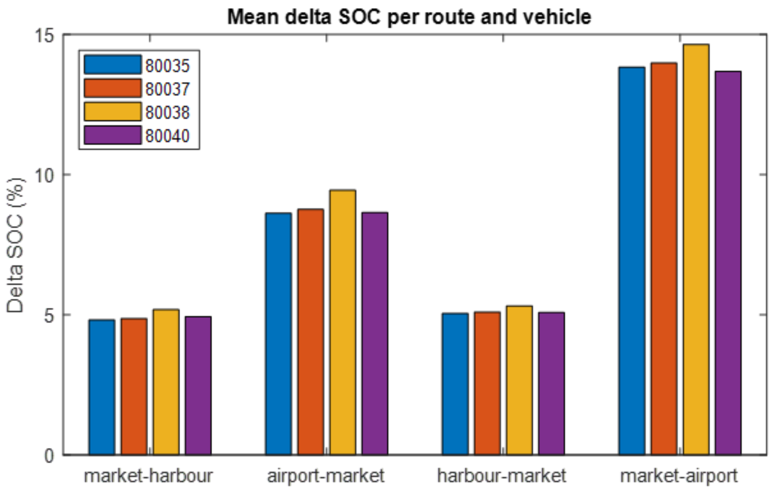

Figure 21. Mean energy consumption (delta soc %) by route segment and vehicle.

Some further non-parametric statistical testing[6] suggests that the difference in consumption is actually statistically significant at a 95% confidence level (Figure 22).

6. *MATLAB Multiple Comparison test, based on Kruskall-Wallis non-parametric test with H0: Each vehicles' consumption comes from the same distribution, alpha = 0.05*

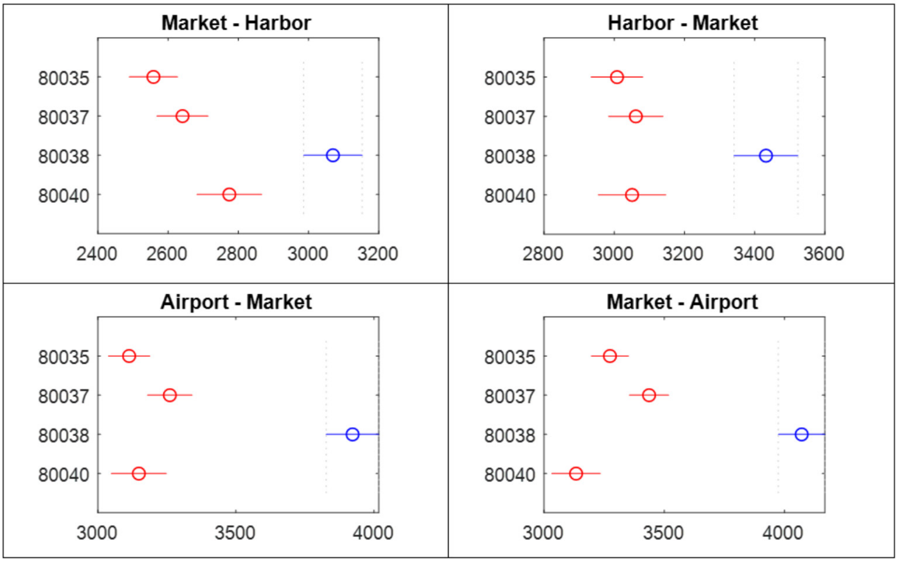

Figure 22. The results from a non-parametric statistical test indicate that vehicle 80038 consumes more energy than the other vehicles on a statistically significant level (alpha = 0.05)

Finally, the relationship between consumption and the time of day[7] was studied by rounding the departure times down to the nearest hour. Unsurprisingly, the results from this analysis suggest that the departures in early morning and evening tend to have a lower consumption, possibly due to less congested traffic. In particular, this effect is prominent when driving in the city central area such as the leg Harbor – Marketplace, which can be observed in Figure 23. The results from the other legs are presented in Appendix 3.

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7. *A more rigorous approach would be to also take in to account whether the day is a normal day or a public holiday, but during this study this detail was disregarded.*

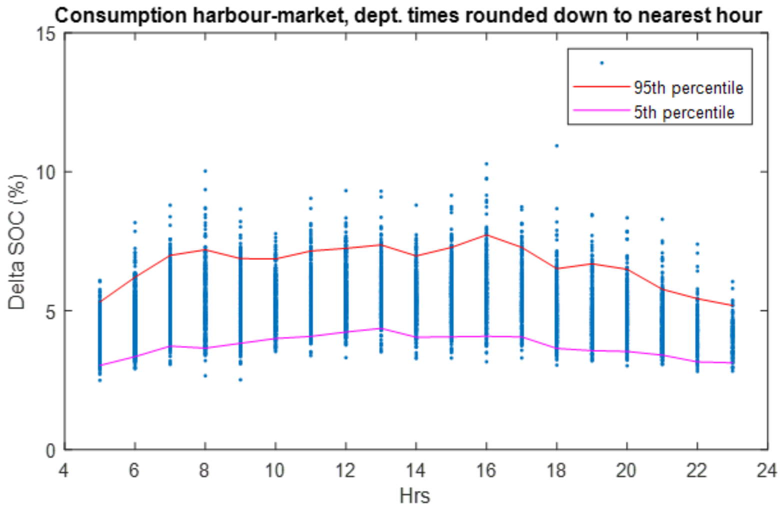

Figure 23. Delta soc vs. the departure time.

4.7 Effect of driving habits and energy consumption differences between drivers

During the data collection period, also an anonymized driver ID was collected, making it possible to connect a driver ID to a single driving instance. This makes it possible to assess not only the variations between vehicles and route segments, but also the distribution of consumption between the drivers. In Figure 24 and Figure 25 we present the quantile graphs[8] showing the distributions on the respective route segments. To make analysis less prone to statistical uncertainty, only those driver ID: s that had recorded at least 30 trips on each route segment were included in the analysis.

8. *Horizontal axis describes the proportion of the driver population that, on average, consumes the amount of energy on the vertical axis.*

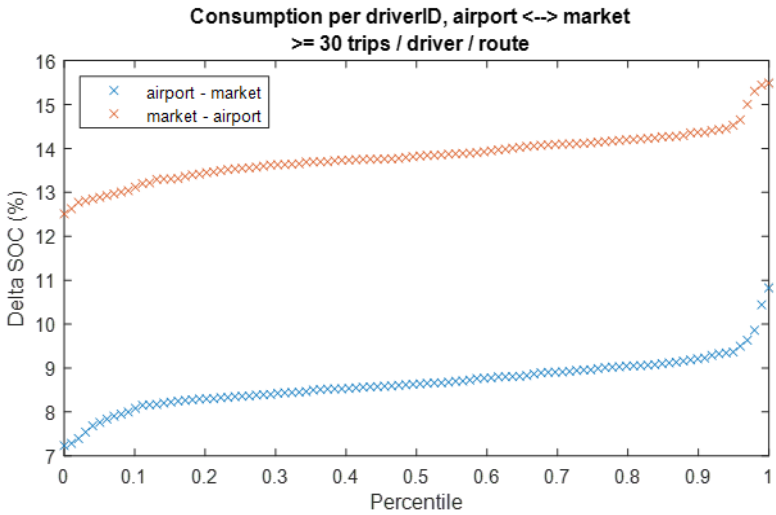

Figure 24. Average delta SOC for driverID, Airport - Market

A fundamental finding in this analysis is that the quantile graphs have distinct "tails" on each end, indicating that drivers are present in the population that deviate significantly from the general population.

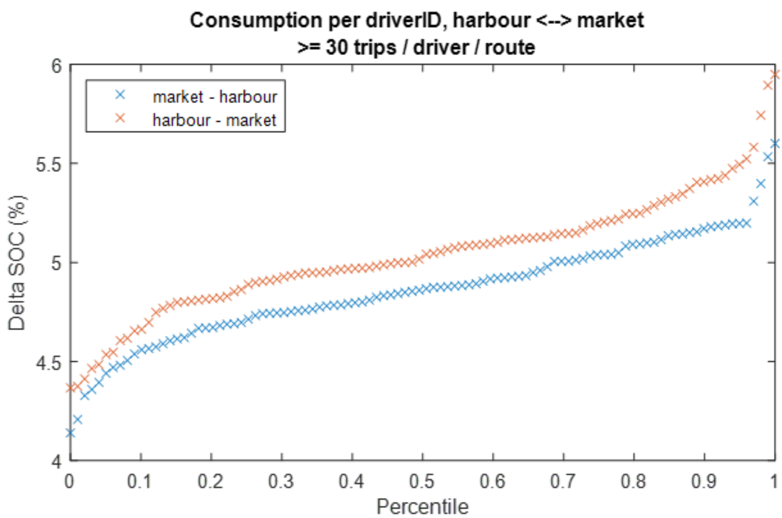

Figure 25. Average delta SOC for driverID, Harbor - Market

Table 9 outlines the same data in a tabulated form. Most importantly, here we observe a difference between the extremes to be 24–50% depending on the route characteristics. A particularly strong variation is shown in the airport – market segment, consisting generally of driving downhill. This suggests that some of the drivers are more successful in employing the regenerative properties of e-bus driving than others.

Table 9. Statistics from energy consumption analysis by driver behavior, unit percentage points

Leg	Min / mean_delta_soc (%-points)	Average / mean_delta_soc (%-points)	Max / mean_delta_soc (%-points)	Max / min ratio
airport - market	7.2 %	8.7 %	10.8 %	1.50
harbor - market	4.4 %	5.0 %	5.9 %	1.34
market - airport	12.5 %	13.8 %	15.5 %	1.24
market - harbor	4.1 %	4.9 %	5.6 %	1.37

For brevity, in Table 10 we convert the values given in Table 9 to the unit kWh by using a static multiplier of 55 kWh for a full battery (100% SOC). However, we emphasize that this is strictly for illustrative purposes and any scientific or technical use is discouraged due to the various nonlinearities existing between the measured SOC and the actual energy content of the battery at a given time.

Table 10. Statistics from energy consumption analysis by driver behavior, approximated as kWh

Leg	Min / mean_delta_soc (kWh)	Average / mean_delta_soc (kWh)	Max / mean_delta_soc (kWh)	Max / min ratio
airport - market	4.0	4.8	5.9	1.50
harbor - market	2.4	2.8	3.2	1.34
market - airport	6.9	7.6	8.5	1.24
market - harbor	2.3	2.7	3.1	1.37

In other words, these drivers consistently performed either significantly better or signifi-cantly worse than average. The difference between the best and the worst driver is roughly in the order of 2–4 percentage points, depending on the route segment. It is plausible that the best drivers are systematically doing some things better, at least in terms of consumption, than those drivers whose results are more mediocre. In Table 11, where we present a summary of top 10 driver ID's on the different routes, we can observe that some same ID's indeed consistently appear on multiple segments. The data in this table is anonymized and not in direct relation to the actual driver ID's collected, let alone the person of the driver.

Table 11. Excerpt of Top10 driver ID's on various route segments. Drivers A, B and C have consistently performed well in terms of energy efficiency.

	Airport - Market	Market - Harbor	Harbor - Market	Market - Airport
1				
2	A		B	B
3	B		C	
4				C
5		B	A	
6	C			
7				
8				
9				
10				A

4.8 External circumstances affecting consumption

Electric bus operation is, in Finnish climate, susceptible to seasonality in the energy consumption. Cold ambient air is known to cause changes in the battery's cell level functions in terms of the battery's ability to deliver and receive current. Also, the resistive forces affecting the vehicle increase while the temperature drops, due to change in ambient air's density and rolling resistance is affected by the snow and (more commonly in southern parts of the country) slush on the road. On a long enough observation window, this seasonality becomes evident, as can be observed from Figure 26. In the summer months, the consumption is clearly lower than in the wintertime.

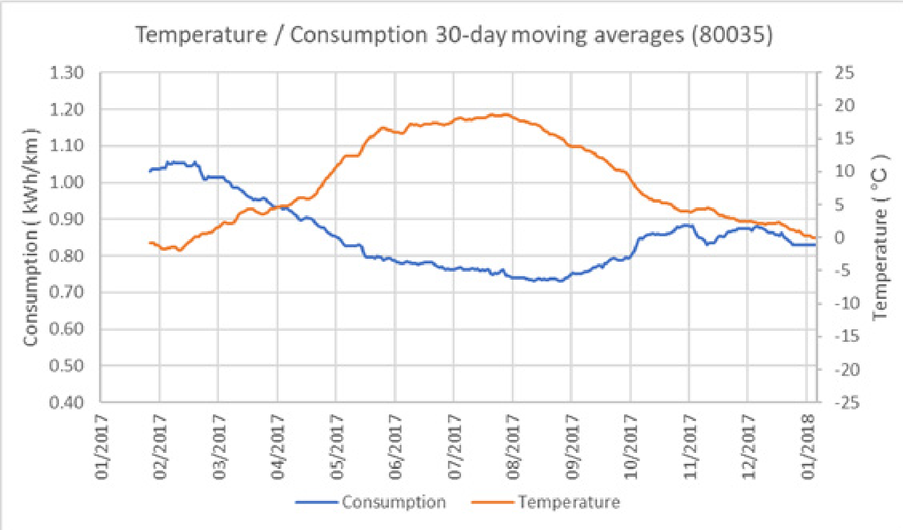

Figure 26. Seasonal trend in energy consumption

On the short timeframe, however, the ambient temperature per se is not a sufficient predictor of the consumption. Instead, the power requirement of a vehicle has to do with many different factors, including the terrain topology, passenger loading (vehicle mass), usage of auxiliaries such as HVAC systems, and perhaps most importantly, the actual speed and acceleration imposed on the vehicle by the driver. To illustrate the complex phenomena involved with the consumption, we present a correlation matrix in Table 12, the raw data of which is extracted from the trips driven on route segment Marketplace – Airport on the period of 9/2017 – 4/2018. Here, we summarize the driver's actions over a given trip by the standard deviation of driving speed.

	Delta SOC	Std. Speed	Driving energy	Ambient temp
Delta SOC	1.00	0.30	0.60	-0.46
Std. Speed	0.30	1.00	0.53	0.16
Driving energy	0.60	0.53	1.00	-0.13
Ambient temp	-0.46	0.16	-0.13	1.00

Table 12. A correlation matrix (point estimates with alpha = 0.05) of the external factors affecting consumption. Value of 1 corresponds to perfect positive linear dependence and -1 to a perfectly negative linear dependence.

Table 12 highlights some of the most interesting aspects about the consumption. Between the temperature and delta SOC there is a weak negative correlation with a weight of -0.46, but also the speed variation (Std. Speed) is correlated with delta SOC with a score of 0.30. The situation drastically changes, if instead of delta SOC we only look at the energy portion consumed by the actual driving motor (Driving energy). To this variable, the ambient temperature has virtually no correlation (-0.13), whilst the speed variation's effect becomes more pronounced (0.53).

Consequently, it can be proposed that the drive motor energy might be a more reliable metric than the overall consumption, in case one wants to ignore the seasonality caused by the fluctuating ambient temperature to the consumption. Here, the energy used to cool or heat the cabin is disregarded, and the variation in drive motor's energy consumption is mostly explained by the variations in the actual driving. This can be an interesting aspect, for instance when evaluating the results of the driver training. In Figure 27 we present a linear fit of the ambient temperature's relationship to the total and drive energy, respectively. In similar manner to the matrix in Table 12, a weak correlation can be observed between the delta soc and ambient temp ($R^2 = 0.21$), while in the drive motor energy's case the correlation is, at least in statistical sense, indistinguishable ($R^2 = 0.02$).

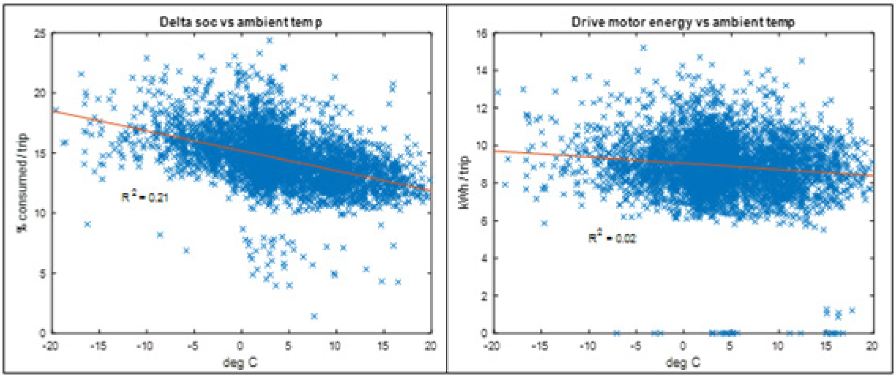

Figure 27. Delta SOC and driving energy vs ambient temperature

Taavetinkangas (2018) makes a similar remark, reporting R^2 scores of 0.62 and 0.37 for the total consumption (Figure 28) and the drive motors consumption (Figure 29) of the Linkker e-buses, respectively, in relation to the ambient temperature. The results of Taavetinkangas are an order of magnitude higher than those presented in this work, which is explained by the longer averaging window[9] and, hence, reduced variance involved.

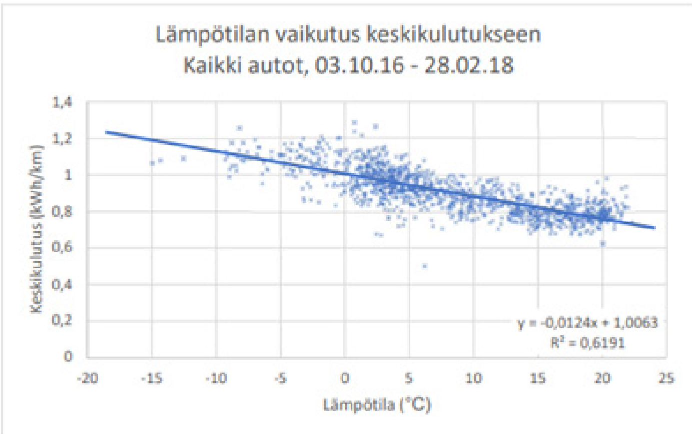

Figure 28. Average daily consumption (kWh / km) vs. average daily temperature (° C) (Taavetinkangas 2018)

9. *Taavetinkangas aggregates the energy consumption to daily average values, while in this work we count each individual trip as an observation of its own.*

Moreover, Taavetinkangas (2018) provides some very interesting insights relating to the temperature dependability of the various subsystems in the Linkker e-bus, such as the HVAC system and the DC-DC converter. Instead of elaborating on them all in detail, the interested reader is referred to the original work.

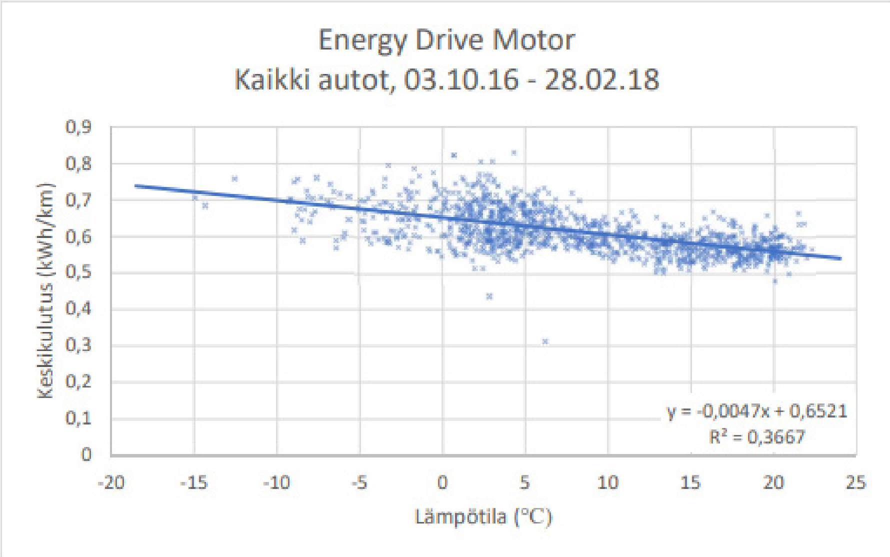

Figure 29. Average daily consumption of the drive motor (kWh / km) vs average daily temperature (° C) (Taavetinkangas 2018)

Similarly to what has been discussed about relationship between temperature and con-sumption, it can be stated that the driving speed variation has a stronger relationship with driving energy consumption than total consumption. By striving to drive at a steady speed, the driver minimizes the amount of braking and re-accelerating, thus saving energy. In Figure 30 we present scatter plots along with linear fits for the total consumption and the drive motor consumption as a function of the speed's standard deviation.

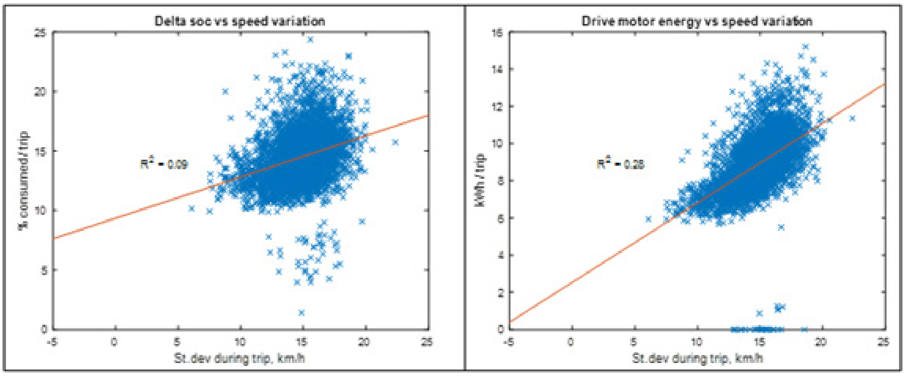

Figure 30. Over all energy consumption and the drive motors energy consumption as a function of the vehicle speed's standard deviation

4.9 Charging station consumption measurements

In order to get a better idea about the system level energy consumption, the airport's charging station power consumption was measured. During the period 12.3.2018 – 5.4.2018, the power consumption was recorded at a 1 Hz rate. An excerpt of the data is shown in Figure 31.

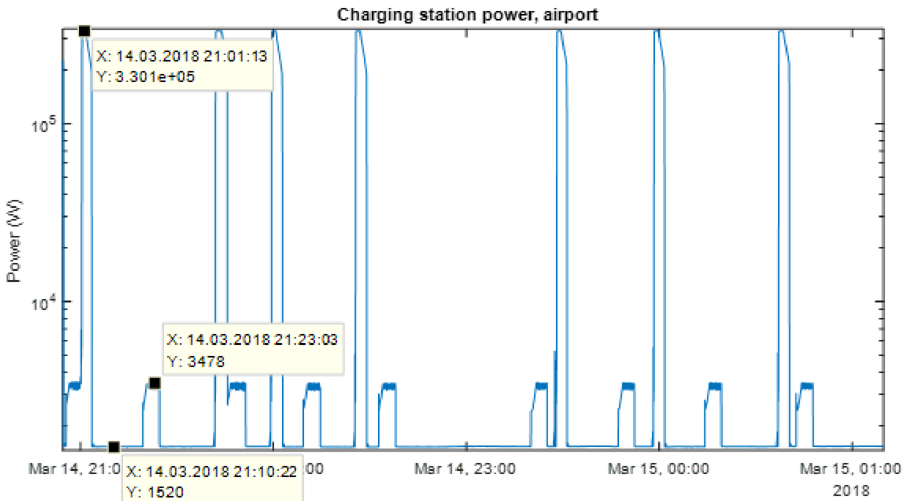

Figure 31. An exerpt of the charging station power measurements

Visual examination of the data suggests there are three distinct modes of operation of the charging station, in particular:

1. Idle loading at around 1.5 kW
2. Periodical load peaking at around 3.4–3.5 kW
3. The actual charging, peaking at around 330 kW.

For the purposes of this analysis, however, we make no distinction between modes 1 and 2 described above. Instead, we classify the charging system at either being at an "idle" or "active" state, depending on whether a threshold of 25 kW is exceeded. The main results from this analysis are summarized in Table 13.

Table 13. Classification of the chargers operation modes during the observation period.

	Total duration (s)	Total energy (kWh)	Mean duration (s)	Median duration (s)	Mean power (kW)	Median power (kW)
Active	215633	16330	186	195	273	288
Idle	1887201	966	1623	958	1.84	1.52
Total	2102834	17296	N/A	N/A	N/A	N/A
Active / Total	10.3 %	94.4 %	N/A	N/A	N/A	N/A

From Table 13 we can visualize some interesting insights regarding the overall system utilization rate and division of the energy consumption between active charging and idling. While, in terms of time, the system has mostly been at an idle state (89.7%) the amount of energy transferred during the idle periods has only accounts for 5.6% of the total consumption recorded. Linearly extrapolating on the 24-day observation period, on a yearly level the system-level (2 fast charging stations) idle consumption would correspond to

$$E_{idle} = 2 * \frac{966\ kWh}{24\ days} * 365 \frac{days}{year} \approx 29383 \frac{kWh}{year}$$

Since the measurements were done in the spring time, with moderate ambient temperatures ranging from -6 to +10 °C (Foreca 2018), the actual year-round consumption might be even higher. In extremely cold climates the heater included inside the charger housing is activated in order to ensure satisfactory conditions for the electronic components inside. According to a representative of the charging system manufacturer, the power requirement of the heater is 6 kW, but the exact temperature limit when the heater is activated remains undisclosed (van der Zwaan 2017). Hence, taking in to account the measured base load in idle mode of 1.5 kW, in the worst case we could periodically expect an idle consumption of 7–8 kW. It would seem, however, that although the measurement period included some sub-zero temperature days, the heater was not extensively used. It can be a different during the winter, when long stretches of extremely cold periods occur frequently.

In Figure 32 we present a randomly selected subset of the events in "Active" class (N = 1161). Examining the data visually, we observe a typical behavior pattern for the charging event: Fast power rise, steady-state phase of varying length at around 330 kW, a ramp down phase, finally followed by a rapid power drop. Over the whole dataset, we compute the mean charging power to be approximately 273 kW and the charging mean duration to be 186 seconds. Since handshake and release times are excluded from this, we conclude the result to be in good agreement also with those presented earlier in this work (Figure 13, p. 29)

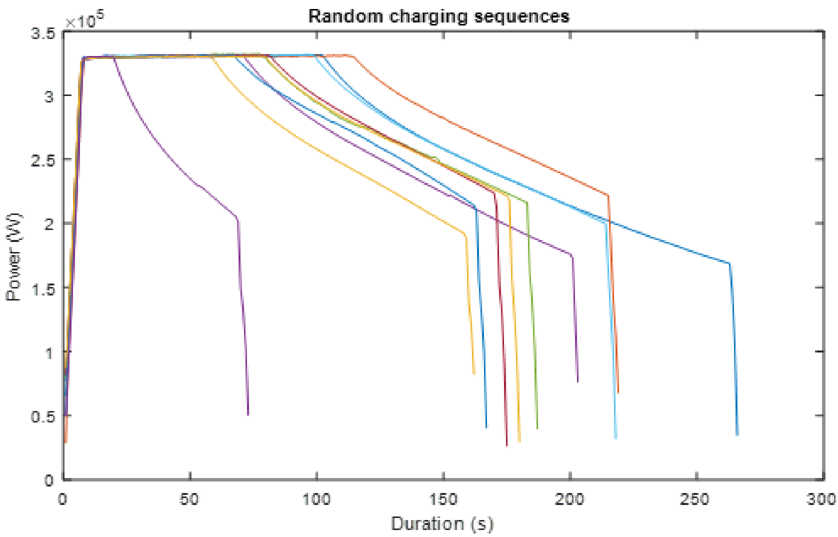

Figure 32. Random charging sequences measured from charger

In Figure 33 we present data similar to Figure 32, but this time measured from the vehicle's system. Key observation here is the peak load, as registered by the vehicle is now located at around 300 kW instead of 330 kW as seen by the charging station. This visual observation suggests a charge-time efficiency of approximately 90%, although no rigorous analysis has been conducted during this study.

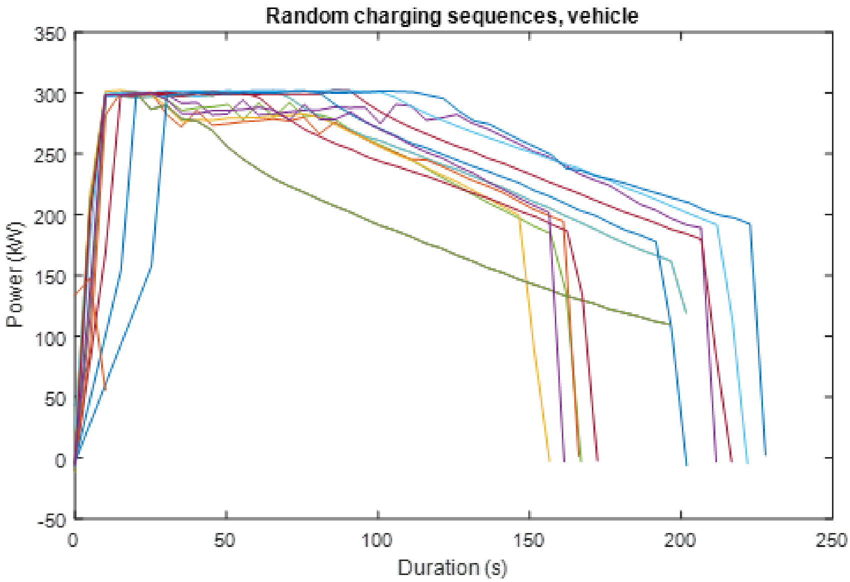

Figure 33. Random charging sequences measured from vehicle

4.10 Chassis dynamometer consumption measurements

To verify the vehicle's compliance in terms of energy consumption with the information provided in the quotation, chassis dynamometer testing was conducted at VTT Tech-nical Research Centre of Finland in June 2017. At the time of writing, only one of the vehicles have undergone testing at VTT, namely, the vehicle number 80035. The tests consisted of various different driving cycles, most importantly the internationally standardized Braunschweig cycle with varying payload. Table 14 presents a subset of the results.

Table 14. Subset of VTT dynamometer measurement results (Anttila 2017)

Test Cycle	Payload (kg)	Net consumption (kWh)	Distance (km)	Duration (s)	Average speed (km/h)	Specific consumption (kWh / km)
Braunschweig	3500	9.302	10.847	1732	22.5	0.858
Braunschweig	3000	8.97	10.871	1732	22.6	0.825
Linja 11	3000	5.939	9.109	1365	24	0.652
ADEME	3000	5.592	5.753	1882	11	0.972
LUB	3000	12.706	16.552	3121	19.1	0.768
Santiago uphill	3000	15.469	9.795	1818	19.4	1.579
Santiago downhill	3000	6.184	10.111	1818	20	0.612

The results are in relatively good agreement with the information provided by the manufacturer at the time of tendering, specifically 0.8 kWh / km for the Braunschweig cycle at 3,500 kg payload. While the consumption measured at VTT does exceed the manu-facturer's initial approximation by 7%, penalties have not incurred for an exception this small. According to the tendering documentation, penalties are only applicable for excessive consumption of 10% or more. (Turun kaupunki 2016)

Furthermore, the results observed in Table 14 underline the effect of the route characteristics on the consumption, particularly, topology of the terrain. For instance, while the Santiago downhill / uphill cycles are similar in distance, duration and average speed – essentially the same route driven to different directions – it comes as no surprise that the consumption is significantly higher when driving uphill. To a lesser extent, we make the same kind of observation in Turku's route segment airport – marketplace, which has significant altitude deviations on route (See Figure 19, p. 38).

Beneficial to Linkker, the vehicle's curb weight measures in at a competitive 10 500 kg, due to lightweight aluminum chassis construction. The gross vehicle weight is 16 000 kg, giving a maximum payload of 5 500 kg. The measurements at VTT were repeated with multiple different payloads. The results, net specific consumption kWh / km as a function of the payload are plotted in Figure 34, revealing a nearly linear relationship between the variables.

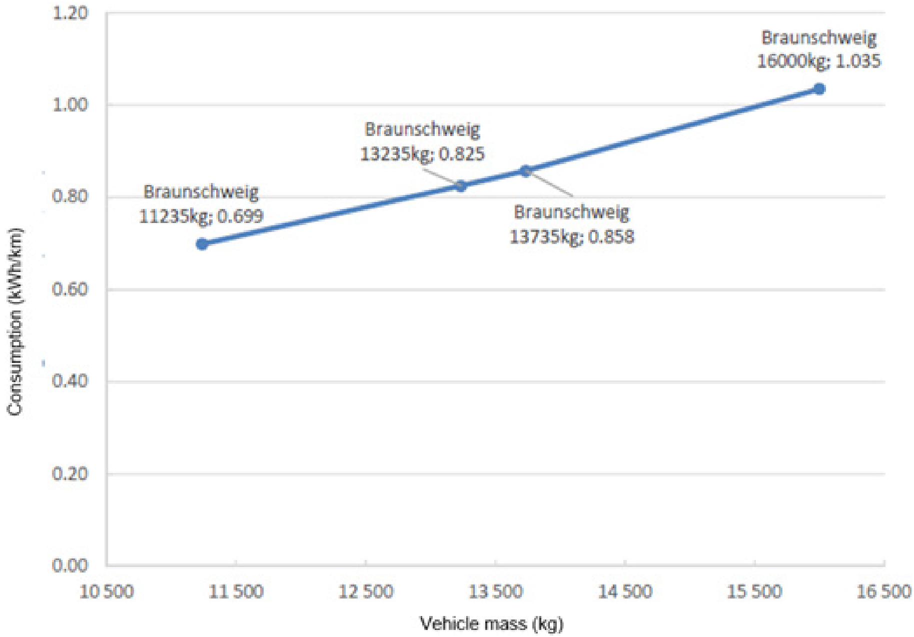

Figure 34. The effect of payload on consumption (Anttila 2017)

For comparison, the consumption of a recently measured Euro V diesel bus of similar dimensions to Linkker, with a 3 000 kg payload has been measured to be in the range of 4.92 kWh / km in the Braunschweig cycle. Linkker's result in the corresponding cycle, 0.825 indicates a nearly six-fold improvement in consumption. (Anttila 2017)

Finally, during the measurements at VTT the e-buses regeneration capabilities were also assessed. During the test cycle, voltage and current at the battery were recorded at 10 Hz rate. From this data, the consumption over the cycle is subsequently computed as a sum of energy consumed from the battery (positive) and the energy regenerated to the battery (negative). Table 15 outlines the results over the various cycles with the 3 000 kg payload, describing the positive and negative energies for each cycle, along with a relative regeneration indicator, given as:

$$\text{Regen }\% = \left|\frac{\text{Battery energy regenerated}}{\text{Battery energy consumed}}\right| * 100\ \%$$

Table 15. Results from VTT dynamometer measurements at 3000 kg payload (Adapted from Anttila 2017)

	Braunschweig	Linja 11	Ademe	LUB	Santiago uphill	Santiago downhill
Battery energy consumed (kWh)	13.801	8.771	8.192	20.4	21.114	13.55
Battery energy regenerated - (kWh)	-4.831	-2.832	-2.6	-7.694	-5.645	-7.366
Battery energy net	8.97	5.939	5.592	12.706	15.469	6.184
Regen (%)	35.0 %	32.3 %	31.7 %	37.7 %	26.7 %	54.4 %

Overall, we observe very satisfactory rates of regeneration, averaging to 36.3% over the cycles. However, the relative rate of regeneration is observed to be highly dependent on the route characteristics, mainly driving style and terrain topology.

4.11 Total Cost of Ownership

The total cost of the ownership model has recently gained traction within the public sec-tor, for it efficiently steers decision-making in public procurements away from the tradi-tional immediate investment price analysis. When electric buses total costs are analyzed, it is of paramount importance to identify which specific cost components owe to the fact that the bus is electric, and on the other hand, which costs would be realized even with traditional diesel vehicles. In this sense, an example of a relevant cost could be the building and infrastructure costs of the charging system. An irrelevant cost is for example the driver's wages, with the (quite realistic) assumption that no premium is paid to the drivers for operating an electric bus instead of a traditional diesel bus.

It is necessary that the electric bus procurement is viewed at the system level. In addition to the vehicles the charging system must be procured, which incurs substantial infrastructure costs. An additional challenge in Turku's case is that buses and the charging system are procured by two separate organizations, specifically Turun Kaupunkiliikenne Ltd and Turku Energia Ltd. If a very detailed TCO analysis was to be conducted, one would technically need to take in to account the boundaries between the organizations and determine from which angle the financial analysis is being done. On the other hand, in the case of public transportation eventually all the costs are transferred to the customers and tax payers. From this perspective, it is justifiable to treat all the costs as equal, not taking in to the account the particular organization who is responsible for each individual cost element.

In his 2017 B. Sc. thesis, Janne Lankila addresses the issue of the total costs of electric bus operation (€/km) on route 1 in comparison with diesel vehicle operation. The charging system and bus investment costs, energy costs and maintenance costs have been taken in to account. The data used in the calculations is based on the Turku City's procurement documents, energy consumption measurements from buses and various expert statements (Lankila 2017, 21–22). In his work Lankila presents a base scenario (Figure 35) along with a sensitivity analysis in respect to various parameters of the operation.

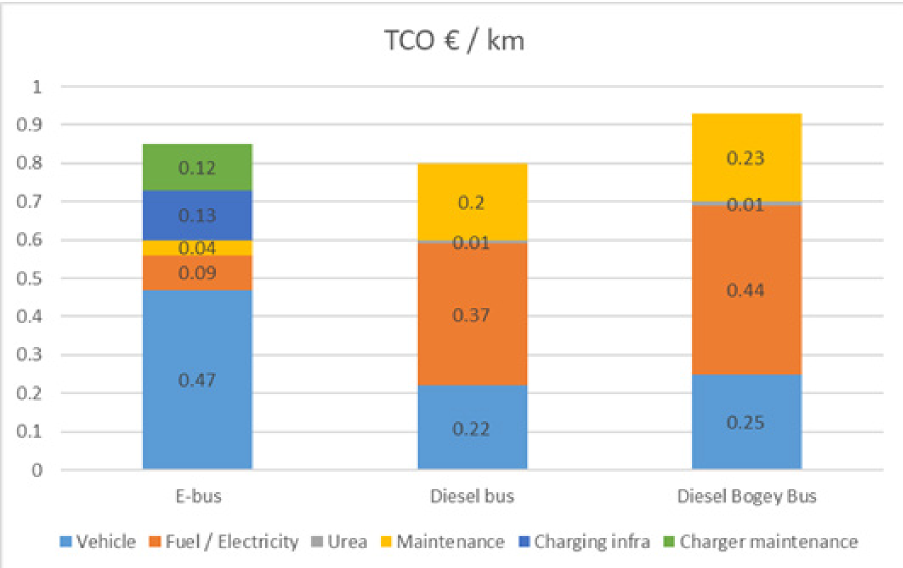

Figure 35. TCO analysis of an e-bus system compared to various types of diesel buses (Lankila 2017)

We observe a base scenario total operating cost of 0.85 EUR / km, slightly lower than corresponding value of a 3-axis diesel bus and slightly higher than a 2-axis diesel. The results are in good agreement with e.g. those reported by Pihlatie et al. (2015), stating a 0.83–0.91 € / km TCO for the electric bus, depending on daily operation range, the lifespan of the vehicle and price of electricity. Furthermore, the results presented in Lehtinen & Kanerva (2017), 0.84 € / km TCO with 100 000 km / year and 15 years lifespan of the bus, are closely replicated. In Lankila's work, sensitivity analysis has been conducted with respect to the yearly driving output and the lifespan of the vehicle, a summary of which is presented in Figure 36 and Table 16.

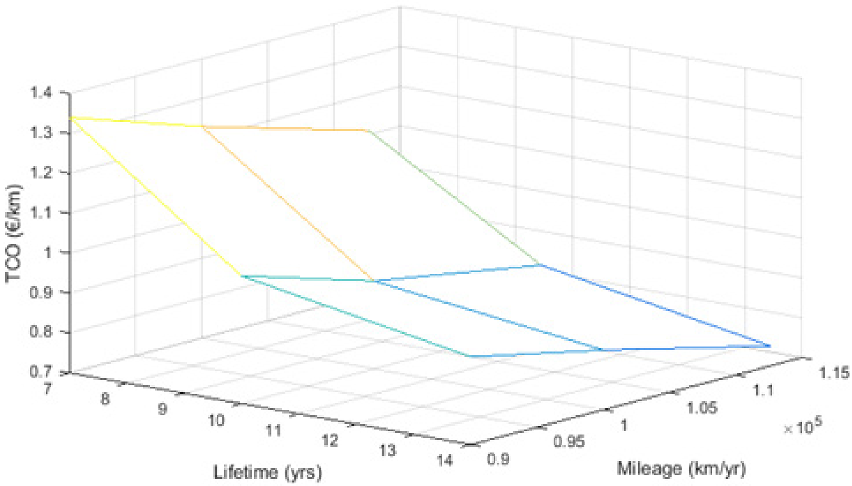

Figure 36. TCO as a function of yearly mileage and the vehicle lifetime in years. (Adapted from Lankila 2017)

Figure 32 approximately outlines the TCO as a function of yearly mileage and the lifespan of the vehicle. While this clearly is an oversimplification for any scientific/ technical use beyond illustrative purposes, it is presented here to underline the notion of maximizing the vehicles' utilization rate in order to achieve economic feasibility.

Table 16. TCO as a function of yearly mileage and the vehicle lifetime in years (Lankila 2017)

	90000 km	100000 km	112611 km
7 v	1.34	1.23	1.11
10 v	1.02	0.92	0.85
14 v	0.92	0.85	0.75

4.12 Environmental impact

As of August 2018, the total driving output of the six electric buses in Turku was 662 211 km. At the time of the eFÖLI project, the majority of buses used in Turku's public traffic were diesel operated buses conforming to the EURO V emission standard. During the project, no emission measurements of diesel buses were conducted, but instead the emissions are approximated from VTT's Lipasto-coefficients (VTT 2017). In Table 17, we present a comparison between the various technologies in terms of the different emission components being generated as well as energy consumed, should the traffic during the pilot phase be produced with traditional vehicles or fully electric.

Table 17. The projected diesel bus[10] tank-to-wheel emissions according to VTT (2017) during the pilot phase (662 211 km's driven) vs. the actual tank-to-wheel emissions from the Linkker bus.

	CO2 (t)	CO2 eqv. (t)	CO (t)	HC (t)	Nox (t)	PM (t)	Energy (MWh)	km's driven
EURO V (empty)	502	513	0.53	0.03	2.78	0.022	2124	662211
EURO V (full)	796	807	0.66	0.04	3.24	0.026	3367	
EURO VI (empty)	502	513	0.19	0.02	0.40	0.002	2124	
EURO VI (full)	796	807	0.20	0.03	0.53	0.003	3367	
EURO V (50 % payload)	***649***	***660***	***0.60***	***0.04***	***3.01***	***0.02***	***2746***	
EURO VI (50 % payload)	***649***	***660***	***0.20***	***0.02***	***0.46***	***0.002***	***2746***	
Linkker 13 BEV	***0***	***0***	***0***	***0***	***0***	***0***	***589.3***	

As a fully electric bus, the Linkker obviously produces no emissions locally, hence having an immediate impact on air quality near the operative routes. From Table 17 it can be inferred that the CO2 tank-to-wheel emission savings of introducing the electric buses on are approximately in the range of 500–800 during the project's pilot phase. In fact, the true avoided emissions depend on the projected payload of the diesel bus, which is illustrated in Figure 37.

10. *City bus in urban driving, GVW 18 t, max. payload 6 t, automatic transmission, empty vehicle = 0 passengers, full vehicle = 43 passengers (VTT 2017). The 50% payload values are computed as linear interpolants between the empty and full bus values.*

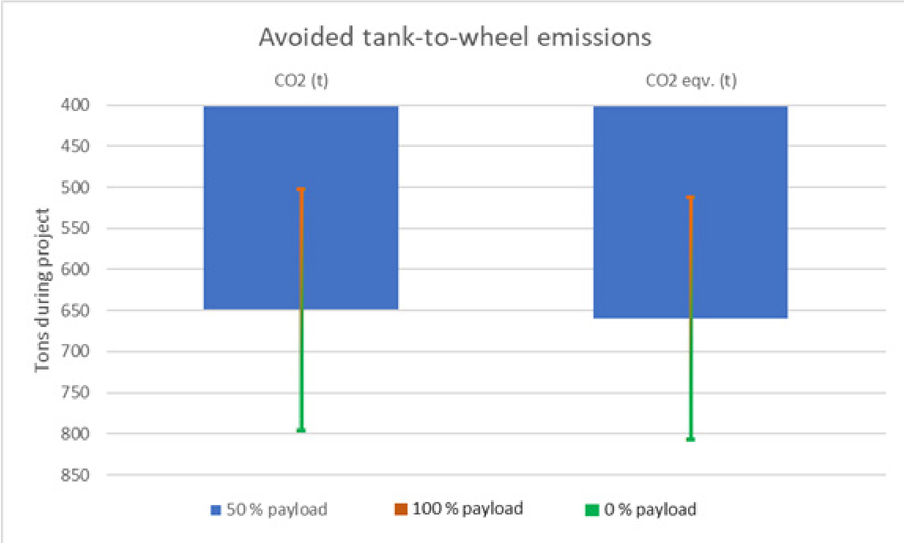

Figure 37. Avoided tank-to-wheel GHG emissions during the project's pilot phase

The other regulated emission components carbon monoxide (CO), hydrocarbons (HC), NOx (Nitric oxides) and particulate matter (PM) are at a very low level already on diesel buses equipped with modern exhaust gas after-treatment systems. On an electric bus, however, these harmful components are mostly eliminated (disregarding the auxiliary heater) which could have an impact on overall air quality in the cities. Figure 38 illustrates the avoided CO, HC NOx and PM emissions due to introduction of e-buses. Once again, the true savings are dependent on the projected passenger loading and fuel heater's emissions are not taken in to account.

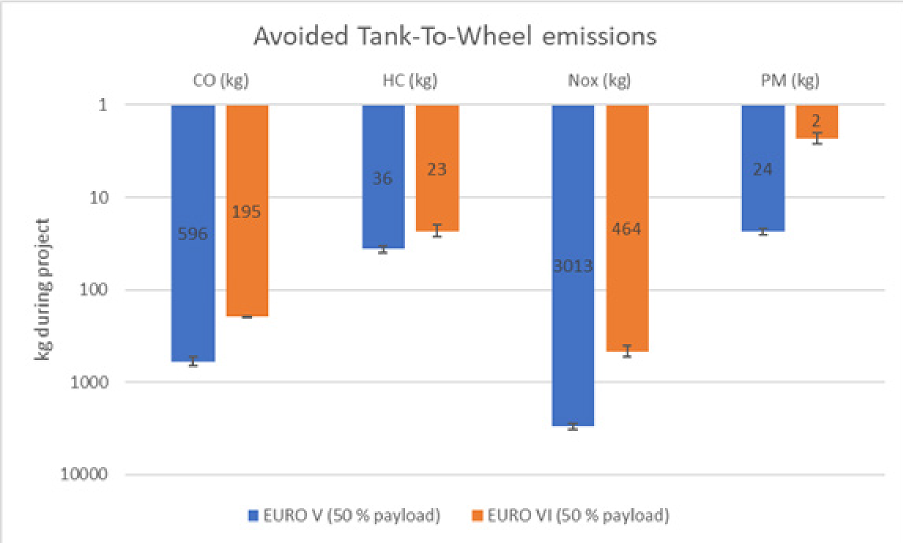

Figure 38. Avoided tank-to-wheel emissions, other emission components

At the system level, the situation is a bit more complex, since the electricity needs to be produced somewhere in the first place and this process usually involves emissions. According to Turku Energia, their energy mix consists of 32% nuclear, 32% fossil and 36% renewable power, which accounts for an average specific CO2-emission of 195 g / kWh. Although actually measuring this is beyond the scope of this project, a rough estimate of Linkker's global "well-to-wheel" CO2 emissions is hence obtained. In Table 18, a well-to-wheel CO2 emission analysis is presented for various fuels and compared with Linkker electric bus.

Table 18. WTW comparison for various vehicle and fuel types. Fuel heater consumption is excluded from calculations.

	Consumption (l / km)	Energy content (MJ / l)	Energy consumption MJ / km	WTW emissions gCO2e / MJ	WTW emissions gCO2e / km	WTW emissions during project (tCO2e)
Euro V/VI, DFO, 50 % payload, optimistic	0.419	35.9	15.04	83.8	1261	835
Euro V/VI, DFO, 50 % payload, pessimistic	0.419	35.9	15.04	96.9	1458	965
Euro V/VI, HVO, 50 % payload, optimistic	0.440	34.4	15.13	8	121	80
Euro V/VI, HVO, 50 % payload, pessimistic	0.440	34.4	15.13	62	938	621
Linkker BEV, Turku energia	N/A	N/A	3.852	54.2	209	138
Linkker BEV, Finnish average	N/A	N/A	3.852	27.8	107	71

In this analysis, we approximate driving on route 1 by a Euro V / Euro 6 bus with a total GWV of 18 tons and maximum payload of 6 tons. For calculations, we approximate an average payload of 50% and hence the average consumption is derived using coeffi-cients extracted from VTT's LIPASTO-database (VTT 2017). Furthermore, we approximate an additional overhead in consumption of 5% when using HVO diesel, due to the lower volumetric calorific value (Neste 2016). Linkker BEV's energy consumption is based on measurements and data analysis made during the eFÖLI pilot project, taking in to account driving-time emission usage as well as the overhead from charging infrastructure, but excluding fuel heater's consumption.

The WTW emission coefficients presented in literature vary from source to source, specifically for HVO diesel fuels the lifecycle carbon footprint is highly dependent on e.g. the feedstock, production method and even the calculation model (VTT 2012; Neste 2018; Neste 2016; Nikander 2008; SFS-EN 16278). In this work, we present optimistic and pessimistic scenarios for the different fuels based on the brief literature survey conducted. In Table 19 a summary is presented of the assumptions and constant values used for computing the figures presented in Table 18.

Table 19. Parameters and constants used for WTW calculations.

Name	Value	Unit	Source (if applicable)
Turku Energia grid electricity	195	gCO2/kWh	Turku Energia 2017
Finnish electricity production12 month average	100	gCO2/kWh	Energiateollisuus Ry 2018
Consumption multiplier HVO/Diesel	1.05		Neste 2016
Fossil diesel energy content	35.9	MJ / l	SFS-EN 16278
HVO Energy content	34.4	MJ / l	Neste 2016
Euro 5/6 consumption, full (43 passengers)	0.324	l / km	VTT 2017
Euro 5/6 consumption, empty (0 passengers)	0.514	l / km	VTT 2017
Diesel, pessimistic	96.9	gCO2e/MJ	SFS-EN 16278; VTT 2012 pp. 9 - 11
Diesel, optimistic	83.8	gCO2e/MJ	SFS-EN 16278; VTT 2012 pp. 9 - 11
HVO, optimistic	8	gCO2e/MJ	VTT 2012 pp. 9 - 11; Nikander 2008 p. 71; Neste 2018; Neste 2016 p. 29;
HVO, pessimistic	62	gCO2e/MJ	VTT 2012 pp. 9- 11; Nikander 2008 p. 71; Neste 2018; Neste 2016 p. 29;
Linkker actual electricity consumption	1.07	kWh / km	Original research
km's driven during project	662211	km	Original research
Vehicle payload factor	0.5		
Conversion factor	3.6	MJ/kWh	

In Table 20 we assess the CO2 footprint of the fuel heater for cabin heating in Linkker electric bus. The analysis is based on the previously computed yearly average Eberspächer consumption 0.030 l / km. The well-to-wheel emission factors from Table 19 are employed. As the table illustrates, the carbon footprint of the fuel heater is non-negligible but is also greatly dependent on the particular fuel being used (Fossil DFO / Renewable diesel).

Table 20. Well-to-Wheel CO2 analysis of operating the fuel heater

	Consumption (l / km)	Energy content (MJ / l)	Energy consumption MJ / km	WTW emissions gCO2e / MJ	WTW emissions gCO2e / km	WTW emissions during project (tCO2e)
Linkker Fuel Heater, DFO optimistic	0.030	35.9	1.077	83.8	90	60
Linkker Fuel Heater, HVO pessimistic	0.032	34.4	1.084	62.0	67	44
Linkker Fuel Heater, HVO optimistic	0.032	34.4	1.084	8.0	9	6

Figure 39 further illustrates the CO2 well-to-wheel emission estimates derived. We conclude that while electricity is clearly, in terms of carbon footprint a very competitive choice compared to conventional diesel fuel, with renewable HVO diesel good results could be obtained too, provided that low-carbon production processes and feedstocks are to be used.

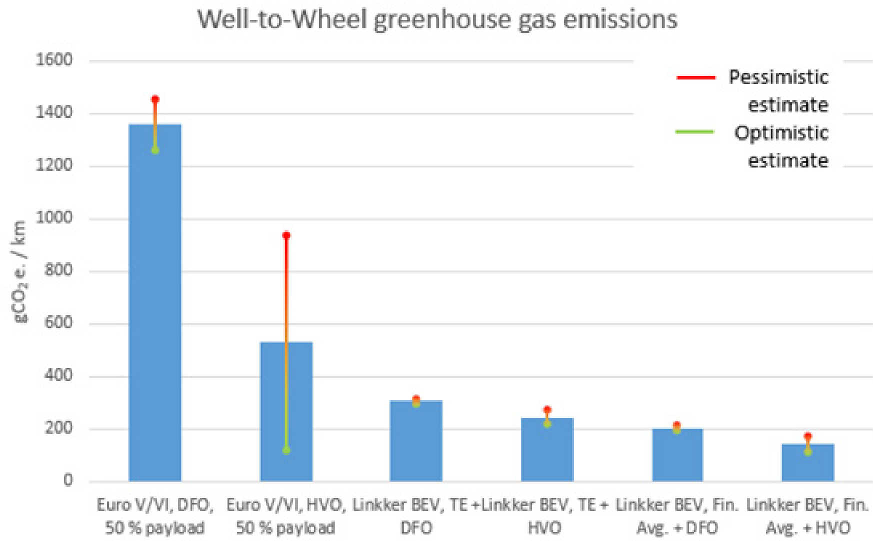

Figure 39. Well-to-Wheel analysis of various fuels of transportation. Linkker values include the operation of fuel heater.

5 Conclusions and discussion

As previously stated, during the first operative years the reliability of the system has failed to reach a satisfactory level. The operation has almost constantly been supplemented with diesel buses due to various interruptions in e-bus operations. Furthermore, according to a statement by the operator's representative, at times there has been difficulty even to get the required spare vehicles on the road.

In projects involving new technology, delays and setbacks are to be expected. According to a view from a representative of the city, in future tendering processes the "learning curve" needs to be significantly steeper. For instance, route 18, which was already analyzed in Lehtinen's (2014) work, is a very high-capacity route, and as such in principle an appealing target for an electrification project. According to City of Turku's representatives, however, the overall reliability needs to be on the level that the possible problems encountered during commissioning can be contained within reasonable limits in order not to hurt the operation too much. Based on the pilot's results, more spare vehicles should also be allocated in order to ensure the route's operation in almost all imaginable scenarios.

In addition to operative difficulties, the image and PR risk associated with poor reliability cannot be understated. Electric buses gaining an initial bad reputation amongst public transport professionals and the general public carries the risk of halting any future developments altogether. This is the case even though not every problem encountered during the pilot project can be accounted to the fact that the bus is operated by electricity. For instance, problems with doors, LCD displays, interior heating and other accessories can, in principle, equally well be encountered in the e-buses' diesel counterparts. Nevertheless, it is easy to imagine how every single repair or maintenance tasks adds to the negative "karma" of the electric buses in the eyes of the bus community and the public. Hence, in the future tendering processes it is of utmost importance that close attention is paid to all the details and aspects of a fully functioning bus system.

On a separate note, a reliably working HVAC system is of utmost importance that cannot be overstated in Nordic conditions. Whatever the buses propulsion system might be, an acceptable level of passenger and driver comfort needs to be ensured in the challenging conditions ranging from massive heat waves in the summer to long stretches of extremely cold winter days. It has even been proposed if the interior heating is something that needs to be separately sanctioned. For instance, representatives of the operator have during the pilot project reported problems regarding inadequate capacity of the fuel heater's (Eberspächer) diesel tank. This is potentially a large issue in wintertime, because during normal operation it is usually impossible to refuel the fuel heater during the day.

In future tendering it will be beneficial to meticulously consider which particular energy consumption metric or metrics are used e.g. in comparing the quotations and determining the possible sanctions. There are multitude of reasons why the simple act of measuring the buses' energy consumption will not be an adequate metric to tell about the system-level sustainability, not even if very accurate methods such as chassis dynamometer measurements are utilized. These reasons account mainly to losses taking place during the active charging process, and on the other hand the charger's idle consumption, which can specifically during the winter months be of substantial proportions. In addition, it is worth noting that the charging equipment in itself might not be fully optimized to function in cold climates. Substantial energy savings could be available in this sector and coordinated communication effort with the equipment manufacturers is suggested to highlight the problems.

With the charging systems having a relatively low utilization rate, the imposed penalty of the idling time to specific consumption (kWh / km) is inherently steep. In fact, as we have illustrated in Ch. 4.3 (p. 30), the system-level consumption as invoiced from the operator by the energy company can be roughly 20–25% higher than the amount of energy that is actually charged to the bus batteries. Based on measurements carried out during the project, the fast chargers are actually able to operate at a > 90% efficiency level at optimal conditions, so this is not where the bottleneck lies, but still actual grid-to-battery efficiency of 75–80% are recorded during the first operative months simply due to low utilization rates. Furthermore, the auxiliary fuel heater's consumption adds significant overhead to the total average system level consumption, as we have illustrated.

In future tendering, the specific consumption problem could be alleviated by economy of scale; that is, making sure maximal utilization rate for the charging systems is reached. The number and placement of the opportunity charging equipment in is an optimization problem of its own, where the objective function of maximizing the charger's utilization is constrained by the requirements imposed by the bus routes and timetables being affected by electrification.

Based on the results of the pilot project in Turku, it is acknowledged that challenges related to new technology need to be addressed in an appropriate manner already in the tendering phase. However, one must be careful not to overcompensate while aiming for a better reliability, as oversized systems and measures can be as costly in terms of overall sustainability as undersized ones. In Turku, the overall impression of the first couple of years of e-bus operation leaves room for improvement. During the pilot project, some invaluable lessons have been learned, and hopefully some of the most common pitfalls can be avoided in future e-bus system tendering processes. At the same time, the system has demonstrated excellent performance in the vehicle core technology's endurance, energy efficiency and environmental impact.

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Linkker
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LINKKER 13
Data sheet

Chassis		
Make	Linkker 13	Low Entry
Size	Length	12818 mm
	Width	2550 mm
	Wheel base	6750 mm
	Front overhang	2754 mm
	Rear overhang	3314 mm
Weight	Curb weight	10.100kg
	GVW	15.500kg
	Payload	5.400kg
Capacity (exemple)	Seats	38 seats + 3 flip-up seats
	Front facing seats	36 seats
	Standing passengers	42
	Total capacity	80
Doors	Door config.	1+2+1 or 2+2+1
	Door dimenisons	850mm or 1200 mm + 1200mm + 700mm
	Door type	Electric, sliding
	Door manufacturer	Tamware
Front axle	DANA NDS 56 LF	
Rear axle	DANA G150	
Tyre size	285/70 R 19,5	
Brakes	Knorr Bremse	
Body	**Linkker LinkLight**	
	Type	Aluminium chassis and body
	Seats	Grammer Inner City or similar. See lay-out drawing for measures
Drive line	**Linkker DriveLink**	
Electric Motor	Permanent Magnet Motor, Visedo	Max power 180 kW, max torque 8.800 Nm at rear wheels Could be increased to 10.000 Nm with rear axle ratio for hilly surroundings (max speed 80 km/h -> 60 km/h)
Drive inverter	Visedo	
Aux inverters	Visedo	

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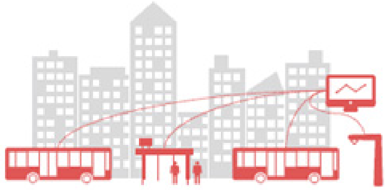
Future Moves

Appendix 1



VCU	**Linkker LinkControl**	Smooth acceleration, vibration free, jolting free, hill stand, wheel slip control etc.
Battery	Actia IM+E	Lithium Titanate Oxide
	Capacity	55kWh
	Recommended charging power	300kW
	Estimated cycles	15.000
	Typical propulsion consumption	Use case 1: 0.8 kWh/km on Braunschweig cycle (payload 3000 kg) Use case 2: 0.6 kWh/km on Espoo bus Line 11 (unloaded)
	Typical range	30-50km
	Charging system	Primary: 300 kW roof connected pantograph (normal or inverted) Secondary: Plug in connection. (Option for 43 kW 3-phase, 400VAC, 63A external service charger and for 3,7 kW on-board charger)
Auxiliaries		
Electric Auxiliaries	Mattei	Air Compressor
	Linkker	Power steering
HVAC		Eberspächer AC136 roof unit
	Type	Heat pump
	Cooling capacity	15 kW @ 30°C
	Heating capacity	15 kW @ 0°C
	Fuel heater (optional)	24 kW

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Figure 1. Linkker 13 side right

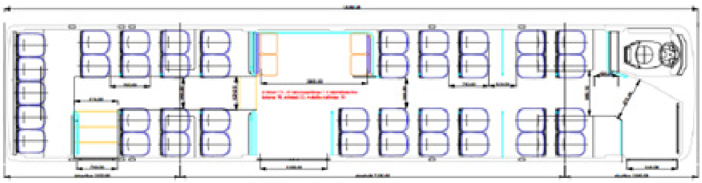

Figure 2. Lay-out example

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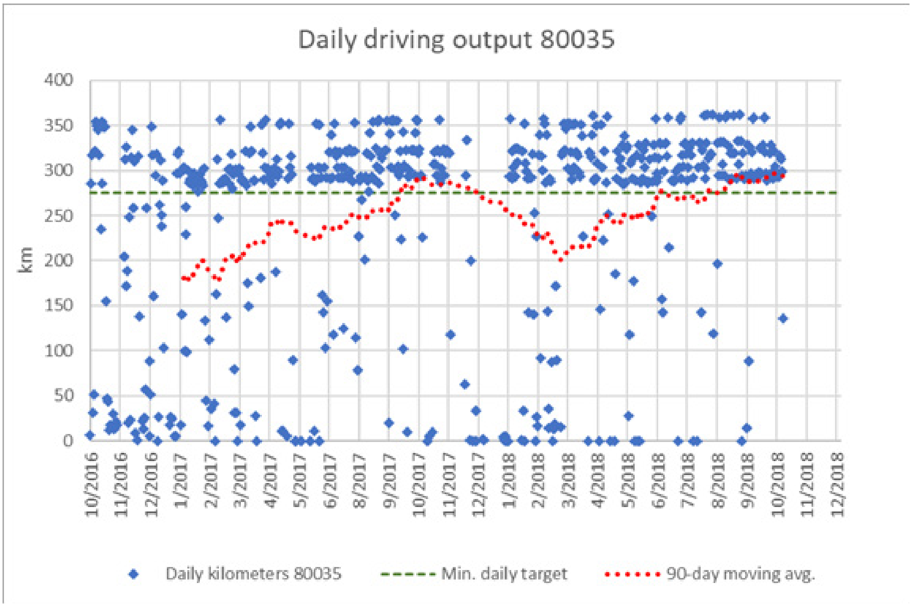
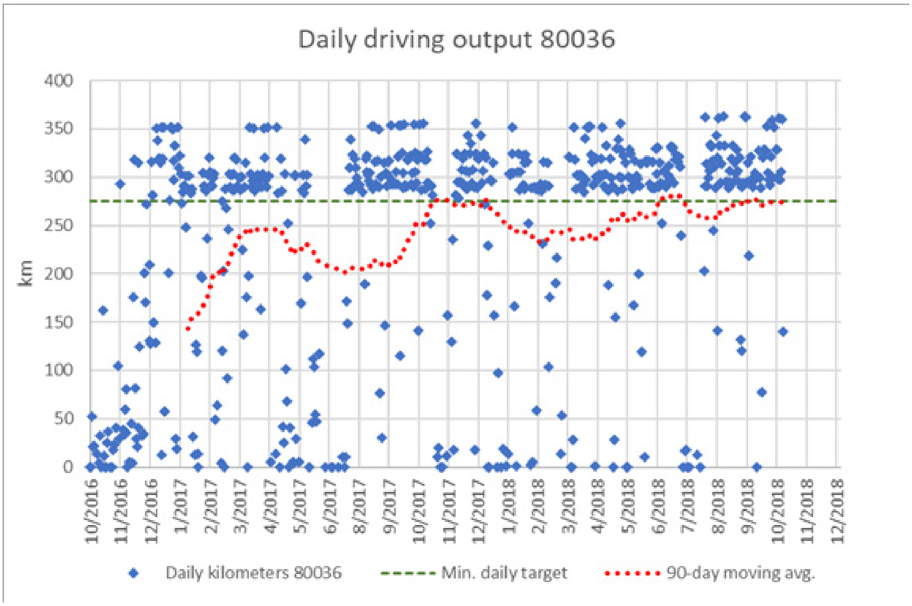
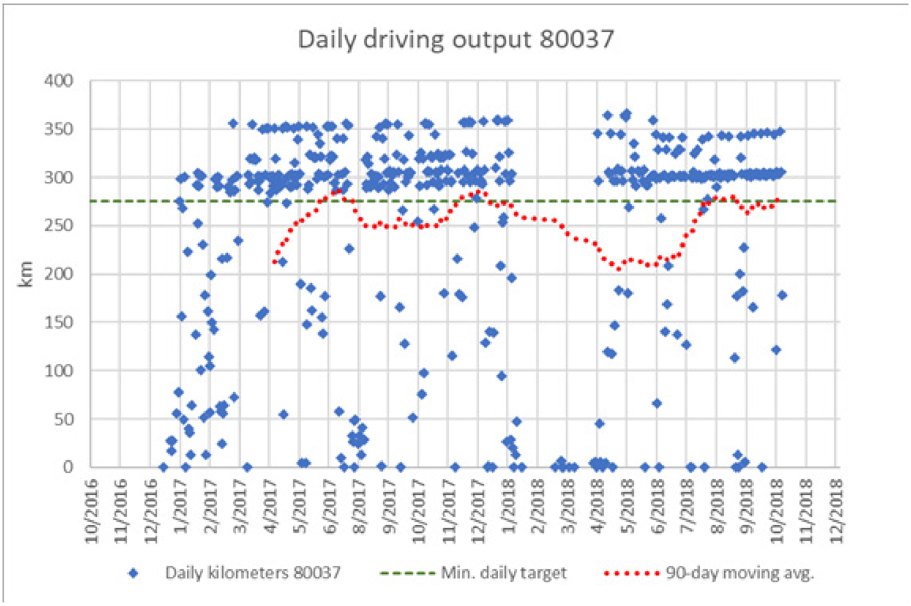
Appendix 2


Daily driving output 80035
400
350
300
250
200
150
100
50
0
km
10/2016
11/2016
12/2016
1/2017
2/2017
3/2017
4/2017
5/2017
6/2017
8/2017
9/2017
10/2017
11/2017
12/2017
1/2018
2/2018
3/2018
4/2018
5/2018
6/2018
7/2018
8/2018
9/2018
10/2018
11/2018
12/2018
Daily kilometers 80035
Min. daily target
90-day moving avg.


Daily driving output 80036
400
350
300
250
200
150
100
50
0
km
10/2016
11/2016
12/2016
1/2017
2/2017
3/2017
4/2017
5/2017
6/2017
8/2017
9/2017
10/2017
11/2017
12/2017
1/2018
2/2018
3/2018
4/2018
5/2018
6/2018
7/2018
8/2018
9/2018
10/2018
11/2018
12/2018
Daily kilometers 80036
Min. daily target
90-day moving avg.


Daily driving output 80037
km
400
350
300
250
200
150
100
50
0
10/2016
11/2016
12/2016
1/2017
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4/2017
5/2017
6/2017
8/2017
9/2017
10/2017
11/2017
12/2017
1/2018
2/2018
3/2018
4/2018
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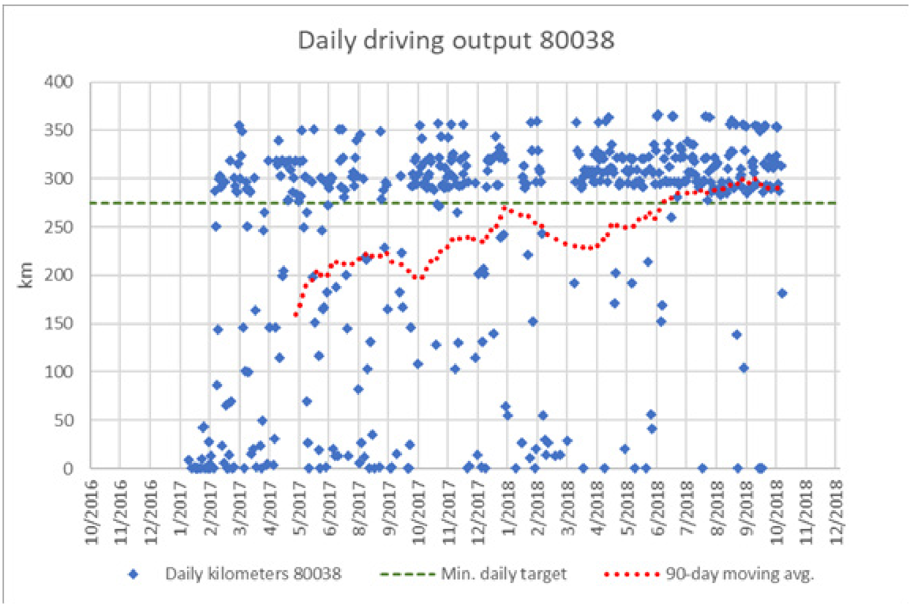
12/2018
Daily kilometers 80037
Min. daily target
90-day moving avg.


Daily driving output 80038
km
400
350
300
250
200
150
100
50
0
10/2016
11/2016
12/2016
1/2017
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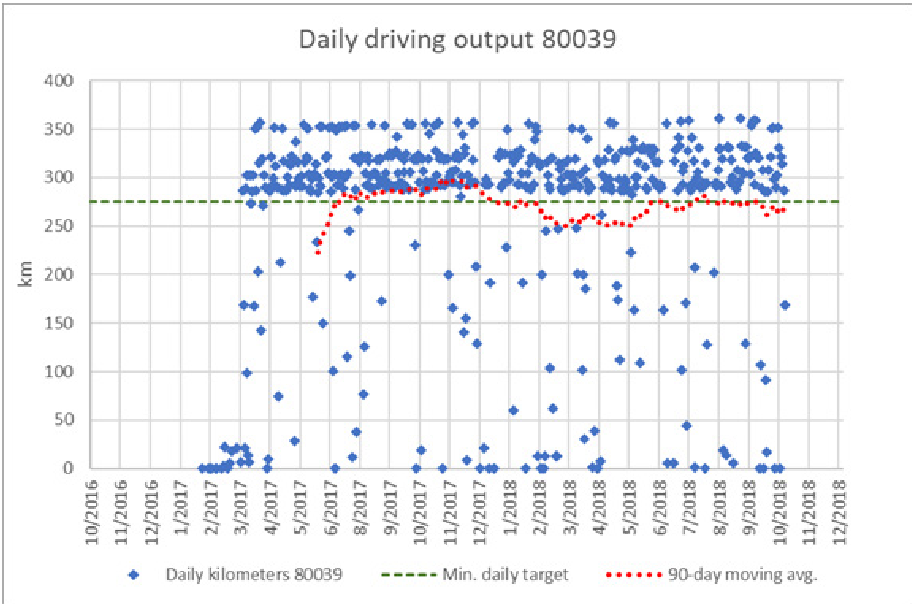
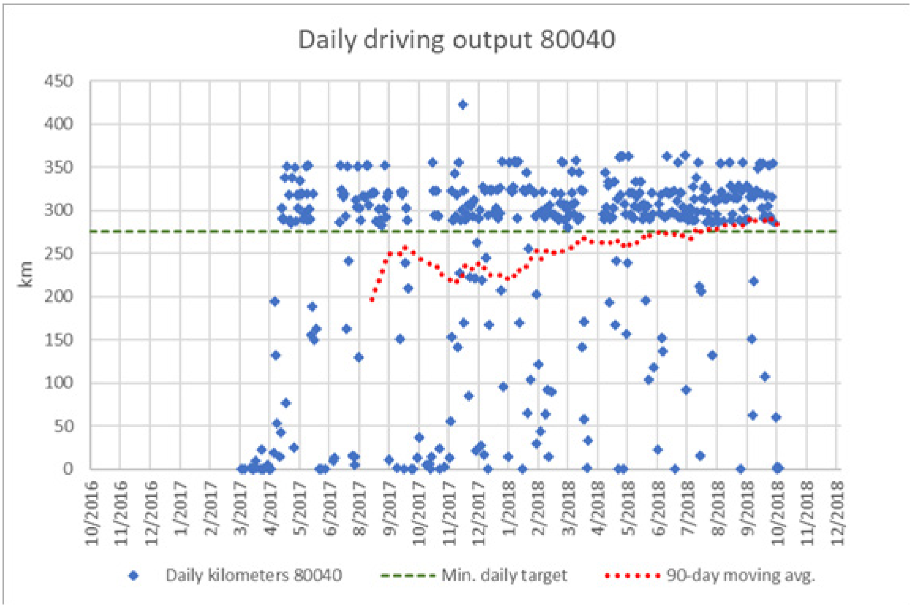
3/2017
4/2017
5/2017
6/2017
8/2017
9/2017
10/2017
11/2017
12/2017
1/2018
2/2018
3/2018
4/2018
5/2018
6/2018
7/2018
8/2018
9/2018
10/2018
11/2018
12/2018
Daily kilometers 80038
Min. daily target
90-day moving avg.

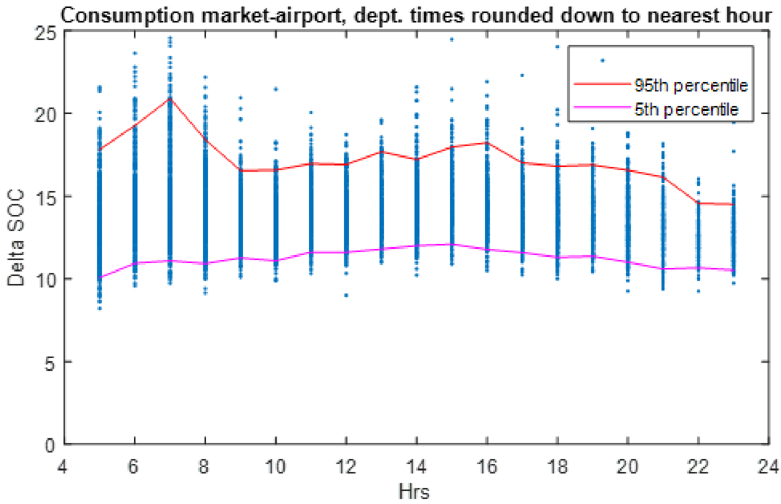
Appendix 2

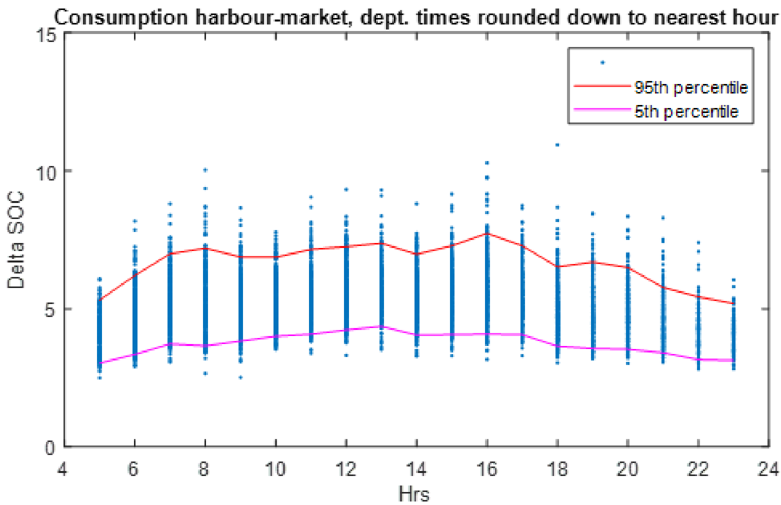


Daily driving output 80039
400
350
300
250
200
150
100
50
0
km
10/2016
11/2016
12/2016
1/2017
2/2017
3/2017
4/2017
5/2017
6/2017
8/2017
9/2017
10/2017
11/2017
12/2017
1/2018
2/2018
3/2018
4/2018
5/2018
6/2018
7/2018
8/2018
9/2018
10/2018
11/2018
12/2018
Daily kilometers 80039
Min. daily target
90-day moving avg.

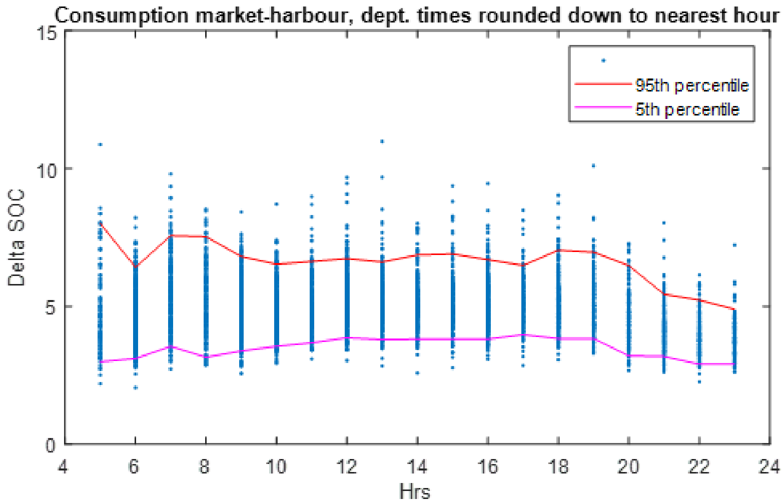


Daily driving output 80040
450
400
350
300
250
200
150
100
50
0
km
10/2016
11/2016
12/2016
1/2017
2/2017
3/2017
4/2017
5/2017
6/2017
8/2017
9/2017
10/2017
11/2017
12/2017
1/2018
2/2018
3/2018
4/2018
5/2018
6/2018
7/2018
8/2018
9/2018
10/2018
11/2018
12/2018
Daily kilometers 80040
Min. daily target
90-day moving avg.

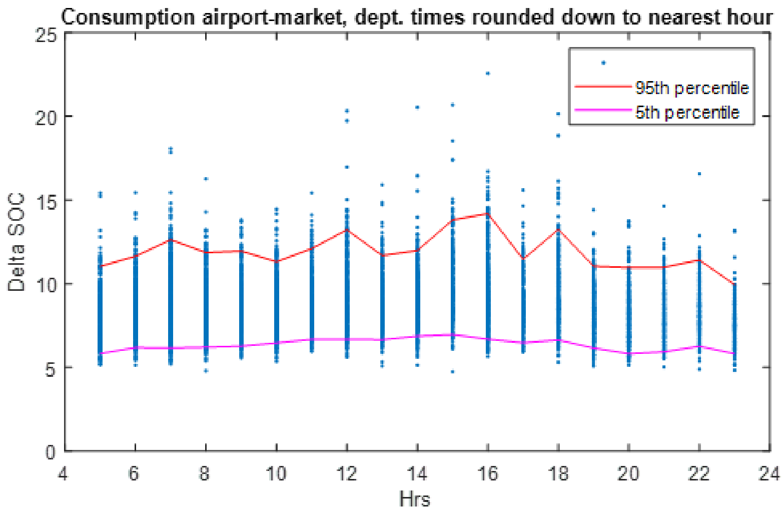

Consumption market-airport, dept. times rounded down to nearest hour
Delta SOC
Hrs
95th percentile
5th percentile
0
5
10
15
20
25
4
6
8
10
12
14
16
18
20
22
24


Consumption harbour-market, dept. times rounded down to nearest hour
Delta SOC
Hrs
95th percentile
5th percentile
0
5
10
15
4
6
8
10
12
14
16
18
20
22
24

Appendix 3



Consumption market-harbour, dept. times rounded down to nearest hour
95th percentile
5th percentile
Delta SOC
Hrs
0
5
10
15
4
6
8
10
12
14
16
18
20
22
24



Consumption airport-market, dept. times rounded down to nearest hour
95th percentile
5th percentile
Delta SOC
Hrs
0
5
10
15
20
25
4
6
8
10
12
14
16
18
20
22
24

Let

$$eff_{total}(d) = \frac{e_{sfc} \cdot d}{e_{sfc} \cdot d + \left(1 - eff_{chg}\right) \cdot e_{sfc} \cdot d + E_{idle}}$$

Compute $\lim_{d\to\infty} eff_{total}(d)$:

$$\lim_{d\to\infty} \left(\frac{e_{sfc} \cdot d}{e_{sfc} \cdot d + \left(1 - eff_{chg}\right) \cdot e_{sfc} \cdot d + E_{idle}}\right)$$

$$= \lim_{d\to\infty} \frac{e_{sfc} \cdot d}{e_{sfc} \cdot d + \left(1 - eff_{chg}\right) \cdot e_{sfc} \cdot d + E_{idle}}$$

$$= \lim_{d\to\infty} \frac{e_{sfc} \cdot d}{e_{sfc} \cdot d\left(1 + \left(1 - eff_{chg}\right) + \frac{E_{idle}}{e_{sfc} \cdot d}\right)}$$

$$= \lim_{d\to\infty} \frac{1}{1 + \left(1 - eff_{chg}\right) + \frac{E_{idle}}{e_{sfc} \cdot d}}$$

$$= \frac{1}{1 + \left(1 - eff_{chg}\right) + 0}$$

$$= \frac{1}{2 - eff_{chg}}$$