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Setting Up and Operating Electric City Buses in Harsh Winter Conditions

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Abstract: The city of Tampere in Finland aims to be carbon-neutral in 2030 and wanted to find out how the electrification of public transport would help achieve the climate goal. Research has covered topics related to electric buses, ranging from battery technologies to lifecycle assessment and cost analysis. However, less is known about electric city buses' performance in cold climatic zones. This study collected and analysed weather and electric city bus data to understand the effects of temperature and weather conditions on the electric buses' efficiency. Data were collected from four battery-electric buses and one hybrid bus as a reference. The buses were fast-charged at the market and slow-charged at the depot. The test route ran downtown. The study finds that the average energy consumption of the buses during winter was 40–45% higher than in summer (kWh/km). The effect of cabin cooling is minor compared to the cabin heating energy needs. The study also finds that infrastructure needs to have enough safety margins in case of faults and additional energy consumption in harsh weather conditions. In addition, appropriate training for operators, maintenance and other personnel is needed to avoid disturbances caused by charging and excessive energy consumption by driving style.

Keywords: electric city bus; energy consumption; winter; weather; temperature; infrastructure; driving style; cooling; heating; emissions

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1. Introduction

Several cities across the world have sustainable mobility plans to reduce carbon dioxide (CO_2) emissions, pollution and traffic jams [1–3]. For example, the city of Tampere in Finland aims to be carbon-neutral in 2030 and wants to find out how the electrification of public transport would help achieve the climate goal. Public transportation, especially in the form of green solutions, such as electrification, walking, and cycling, can have an enormous effect on reducing CO_2 emissions [4]. The European Commission's 2016 strategy towards low emission mobility includes zero-emission vehicles, such as fully electric cars [5]. Research shows that electric buses produce up to 75% fewer emissions than conventional diesel buses [6]. However, fewer emissions are determined by the grid emissions of the used electricity [7]. Electric buses can also decrease the city transport noise [2,8]. Some studies have also mentioned that electric buses are more comfortable than buses with combustion engines [9].

Electric city buses are still a fairly new phenomenon in city transport. Less research has been conducted on testing electric city buses in various climatic zones. For example, in Finland, the temperature can vary from +35 °C to −35 °C [8]. It is of utmost importance for city traffic planners to understand how electric buses perform in different ambient temperatures [10]. This understanding forms the basis for making other crucial decisions related to electric city buses, such as investment costs, the number of buses, charging stations and routes [11,12]. It needs to be noted that the electric buses' procurement cost is still higher than buses with conventional combustion engines [13].

A research gap exists as less is known about the effects of ambient temperature change on the efficiency (vehicle fuel economy) and range of the city buses in cold climatic zones. In addition, less is known how to operate city buses in hard winter conditions. Therefore, this study aims to understand how to operate battery-electric buses in a city located at latitude 61.3 North, where temperature varies between +32 °C and −32 °C, and buses need to operate on snowy and icy street conditions. In addition, the study aims to understand how electric buses perform in such conditions.

This study collected and analysed weather and electric city bus data to understand the effects of ambient temperature, driving conditions and weather on the efficiency (vehicle energy economy) and range of the city buses in the city of Tampere, Finland.

2. Theoretical Background

2.1. Challenges and Opportunities for Wider Dissemination of Electric City Buses

Previous technology-driven research has covered various crucial aspects of electric buses, such as the performance of battery technologies [14,15], energy-efficient heating, ventilation, air-conditioning (HVAC) systems [16,17] and optimised charging infrastructure settings [18–23]. For example, Cho et al. [14] studied the time-dependent low-temperature power performance of a lithium-ion battery. Their study shows that the interfacial charge-transfer resistance of the anode (graphite) and the cathode (lithium cobalt dioxide) greatly impact the low-temperature power decline. Other non-technical studies have focused on incentives, such as contracting and financing mechanisms, to increase the adoption of electric buses in cities [2,13,24]. For example, Li, Castellanos, et al. [13] found three contracting and financing mechanisms to accelerate electric bus adoption: (1) public and private grants, (2) less costly sources of financing and (3) innovative ways of structuring contractual implementation.

Several studies have also examined the lifecycle assessment (LCA) of the energy and carbon dioxide emissions and calculated lifecycle costs (LCC) of city buses [6,7,12,25–27]. For example, Meishner and Sauer [12] conducted an economic comparison of four different battery charging methods based on the total cost of ownership (TCO), including all investment and operating costs in the bus service. They found that electric buses are economically competitive under favourable conditions. Topić et al. [28] developed a simulation tool to calculate the optimal type and number of buses and charges and predict the TCO of city bus fleets. On the other hand, Bi et al. [26] created an integrated LCA and LCC model to compare the lifecycle performance of plug-in charging versus wireless charging of an electric bus system. It turned out that the wireless charging bus system had the lowest LCC per bus kilometre and had the potential to reduce use-phase carbon emissions due to the light-weighting benefits of onboard battery downsizing compared to plug-in charging [26].

Based on the previous studies, the wider dissemination of battery electric vehicles (BEVs) in cities requires two decisions by authorities. The first is that the city decision makers identify the right contracting and financing mechanisms for replacing conventional buses with BEVs. The second decision is selecting the optimal infrastructure setting for electric city buses. For example, some buses can run almost the whole day with a big enough battery. In contrast, other buses are slow or fast charged in specific charging stations, overnight or in dedicated bus stops. Some researchers have created models for determining the optimal number and location of required charging stations for a bus network and the adequate battery capacity for each bus line [10,18,29,30]. Some studies also report efforts to quickly change the battery in a battery-changing station [20]. In addition, wireless charging technology for electric buses might be an option in the future [26].

2.2. The Effect of Ambient Temperature on Electric City Buses' Electric Consumption

It is already widely communicated that the range of electric vehicles varies with temperature [31]. Research results also confirm this observation. For example, previous studies have shown that the range of electric buses decreases a lot as the temperature drops below zero degrees [32]. This happens because the functioning of the lithium-ion battery varies with temperature [14]. In 2015, Graurs et al. [33] studied public electric bus energy consumption during the coldest months in Latvia (Jan-Mar) and found that the bus consumed 2.86 kWh per kilometre. In 2015, a study estimated that an electric bus with a light aluminium chassis (9000 kg curb weight) consumed on average 1 kWh/km [34]. Electric Commercial Vehicles project (2012–2016) reports that the voltage drop caused by the internal impedance and the applied current at cold temperatures is the reason for reduced battery capacity [8]. In addition, Henning et al. [32] report that temperature drops from around 10.0 °C to around 0 °C caused battery-electric buses to lose around 32.1% of their battery capacity. Another study found that ambient temperature impacted energy consumption a lot in the case of a DC/DC-converter, heat pump and drive motor [35]. However, power steering and an air compressor did not have an insignificant impact.

Ambient temperature and several other factors influence the range of electric buses, such as topography, the road pave (sand, concrete), and the road's surface conditions (wetness, snowfall, sleet, ice). Bartłomiejczyk and Kołacz [36] studied the relationship between ambient temperature and demand for heating power. They found that traffic congestion can result in a 60% overall increase in energy consumption. They also found that auxiliaries may consume 70% of the electric bus's energy during winter, whereas they generally consume almost 50% of total energy use [36]. In addition, the driving style affects the use of energy. For example, fast accelerations consume lots of energy [20]. Preheating the battery and indoor air before starting the bus, on the other hand, saves energy [16]. However, heating the bus cabin during the drive also reduces the range. Research shows that heating and cooling can consume 35% of all energy in electric cars [37]. While the energy consumption of an electric bus increases, the battery's state of charge and the travel range are reduced [38]. Therefore, researchers have proposed a fuzzy braking strategy of which electricity consumption was shown in a simulation platform to decrease by 9.8% compared to the normal braking energy management control strategy [39]. Then again, using a novel sorption air conditioner was shown to save cruising electric vehicles' mileage by 100 km [40].

The bus body and insulation materials also impact how efficiently a bus passenger cabin is kept warm or cool, which again affects the energy usage of the bus [32]. For example, Chiriac et al. [41] estimated that the average energy demand due to ambient heat loss of bus structure and opening the doors at the stops was 12–14 kWh. The bus was 12-m long, had 100 passengers and three doors, 150 kW electric traction motor and 33 kW installed power for the heating system [41].

3. Case Study

This paper adopts a case study methodology to describe the procurement and operational models used for setting up the needed technical infrastructure for electric city buses and operating those buses in a cold climatic zone to understand the effect of this climate on the energy use of buses. A single case study approach [42] was adopted because it well suits the study of a topic that is not yet well explored.

The city of Tampere in Finland aims to be carbon-neutral in 2030. Currently, the traffic is accountable for about a quarter of the city's carbon dioxide emissions. In 2019, an amendment to the Clean Vehicles Directive came into force. The amendment obliges the public sector to procure zero-emission vehicles. The city of Tampere is one of the lighthouse cities of the EU-funded STARDUST project where new solutions for reducing emissions are piloted. In Tampere, the focus is on reducing emissions from public transport and supporting light transport. Furthermore, the 2017 climate strategy of the Finnish Government necessitates a 50% reduction, compared to the year 2005, in transport greenhouse gas (GHG) emissions by 2030 [43]. Thus, the cities in Finland are encouraged to electrify public transportation.

Nysse is the Tampere regional public transport organisation in Finland. It had around 41,300,000 passengers in 2019. In 2020, the number of passengers was lower due to COVID-19, which made people remote work. Nysse serves an area that includes eight municipalities where approximately 390,000 inhabitants live. About 60% of bus services are outsourced to three major private operators, and in-house operator drives around 40% of bus services. Nysse has 280 buses in operation.

The climate in Tampere is cold and temperate can vary between +32 °C and −32 °C. The lowest average temperature is −8.2 °C in February, and the average temperature is 16.0 °C in July. The average annual temperature is 3.7 °C.

In Tampere, electric city buses were introduced at the end of 2016. A test system was created to collect data on electric buses. Initially, a meter was placed in one bus for sensing energy efficiency. Later on, measuring equipment was installed on three other electric buses. When problems in setting up the data collection were tackled, the data has been collected for more than two years, including a couple of winter seasons.

Since 2017, electric buses have been operating in the city of Tampere's bus route 2, which starts from Pyynikintori market and ends at Rauhaniemi. The round-trip length is around 8.8 km. The buses are fast-charged at the market and slow-charged at the depot. The buses spend the night inside a warm depot; thus, the buses' interiors are warm when they leave.

Data were collected from four battery-electric buses and one hybrid bus as a reference. The electric buses were model Solaris Urbino 12 low entry, with an autonomy of approximately 60 km. The electric buses used lithium-titanate (LTO) batteries of 3 × 25 kWh that last at least 10 years and demand 0.5 h for a total fast charge. The maximum speed of the buses is over 70 km/h, and the average consumption is 100–150 kWh each 100 km (without heating). Buses have 32 fixed seats, four-fold seats, and 46 standing spaces. The dimensions of the buses are the following:

- Wheelbase: 5900 mm
- Length: 12,000 mm
- Width: 2550 mm
- Height: 3300–3480 mm
- Curb weight: 14 t
- Max torque: 973 Nm
- Max power: 250 kW

Data was collected with WRM-247 of Wapice Ltd. for three years, between January 2017 and August 2021. The following data was collected by the meter in real-time: latitude, longitude, speed, energy consumption, charging time, temperature, battery's state of charge, battery power and distance travelled. The typical sampling frequency was 1 Hz.

WRM-247 devices allow remote management, measurement and control. They were purchased and installed by the STARDUST lighthouse project. One of the e-buses already used this device, so the other three e-buses and the hybrid bus were equipped with the same devices to achieve comparable data. The buses' mobile networks (3G/4G) were used as the connectivity layers towards the server that collects the data. The aim was to also have the same equipment on the charging platform to acquire more accurate information about the charging of the buses.

The data from the WRM-247 devices was sent to an IoT-Ticket instance, which is an IoT platform product by Wapice. City's Azure logic app checks the IoT-Ticket REST API for new data once every two hours and transfers all the new data to City's Azure blob storage. From there, the data is aggregated and stored in Azure SQL database. Data analysis from the stored data is carried out and presented in a dashboard using Microsoft Power BI. Datasets are shared via a REST API. Figure 1 illustrates the architecture of the e-bus data in the city's Azure.

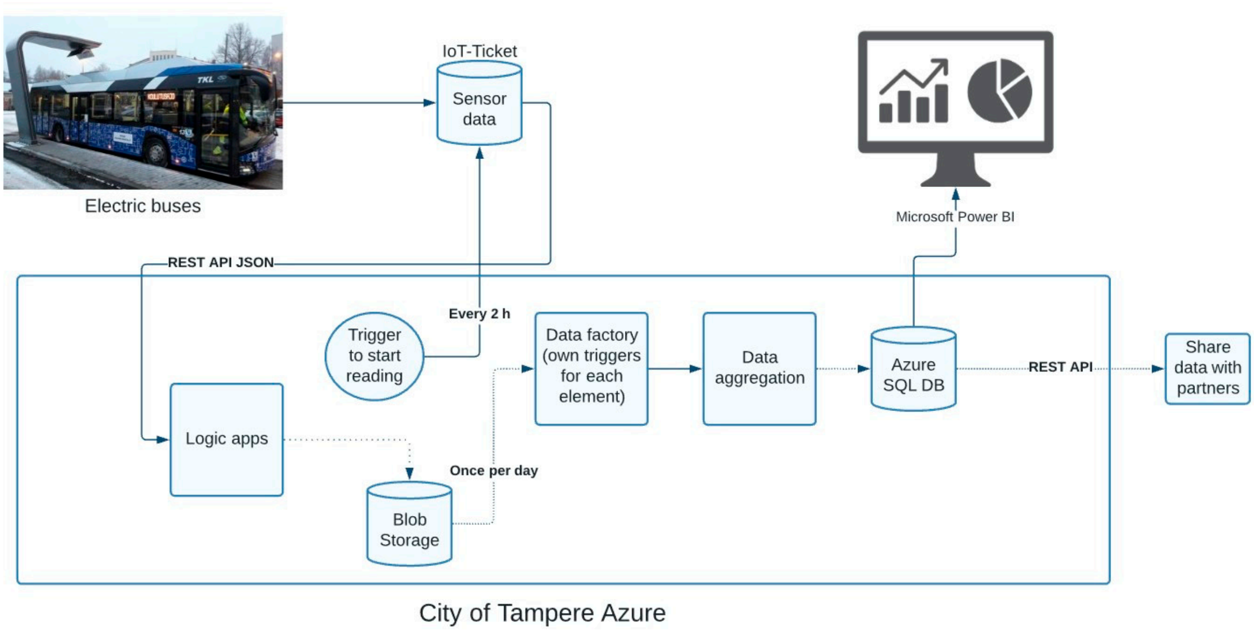


Figure 1. The architecture of the e-bus data in the city's Azure.

In addition, two interviews were conducted in December 2021 to understand the operation of the electric bus system. The purpose of the interviews was to form an overall picture of the operation and find out whether there were any challenges in the charging system or the operation of the buses related to winter conditions. Both interviewees work in the city of Tampere, and they are experienced experts in city transportation and urban environmental infrastructure systems such as maintenance. The interviews focused on specific questions that emerged during the setup phase of the charging system and measurement data-analysis process. Each interview lasted around one hour, and they were not recorded, but detailed notes were taken. The failure situations have also been collected and listed in an excel document throughout the operation period.

4. Results and Discussion

This section first reports the procurement and operational model of the electric city buses in Tampere, Finland. After that, the section presents the results regarding the energy consumption of the buses and explains the energy monitoring and estimation in detail. Finally, the section discusses the energy consumption of the buses and the charging strategy.

4.1. Procurement and Operational Model of Electric City Buses

Tampere has been travelling by public transport since 1948. The City of Tampere Transport Authority—now Tampere City Transport, better known as TKL—operated the public transport service for half a century. A new era of public transport started in April 2006, when it was organised with a subscriber-producer model and brand "Nysse" was born to Tampere public transport. In addition to customer service, planning and administration departments were located in the subscriber unit. TKL stayed to provide a transport service. At the same time, some bus lines began to be put out to tender for private transport producers. The name of the comprehensive service was Tampere Public Transport.

Several parties were involved in preparing and implementing the electric bus system procurement; Tampere city was the main implementer of the procurement project (Figure 2). The buses were acquired and operated by TKL. The public transport planning was responsible for the procurement of the charger. The City of Tampere's public transport unit acted as a subscriber to electronic transport. At the beginning of the project, the City of Tampere's ECO_2 project worked as a leader and coordinator. Inter-city co-operation was also used in the preparation of the acquisition. The collaboration during the acquisition preparation deepened with establishing a joint Forum eKEKO (Extended Management Team for Electric Bus Projects) headed by VTT. In the forum, Finnish cities working with electric buses and VTT as an organizer shared experiences about electric bus operation. Sharing experiences and deepening knowledge, especially with Helsinki and Turku, has been enlightening, especially from the operator's point of view.

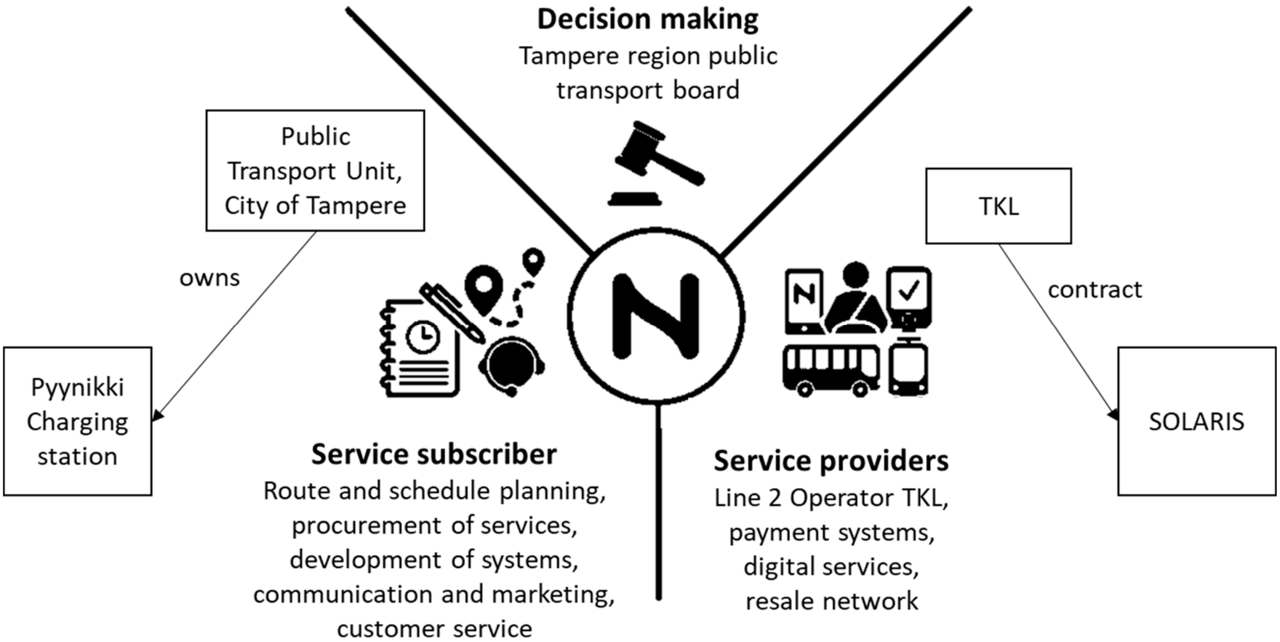


Figure 2. The parties involved in preparing and implementing the electric busses' acquisition.

Figure 2 illustrates the operational model of the electric bus system in the subscriber-producer framework. The city owns charging stations. The procurement process was felt to be easier to start when the city decided to make the charging station investment itself. The supplier is responsible for its maintenance for the five first years, and the charging station also has a warranty. TKL signed a contract with Solaris to lease the four e-buses and maintain the charging stations. The companies Ekoenergetyka and Schunk acted as charger suppliers. The buses used roof-mounted pantographs Schunk SL102.

The tender for the electric bus system of line 2 was opened on 1 July 2015, and the offer period ended on 30 September 2015. With the competition, Tampere became the first city in Finland to acquire an electric bus system through an open tender. Tenders were initially reviewed, and a supplier was selected in October 2015. Tampere decided to ask for a tender for a five-year leasing agreement. At the end of the deadline, Tampere could have decided to buy the buses in a case seen as feasible and reasonable.

The city bought a study that showed that choosing the line in economic terms necessitates making decisions on the following questions [44]:

- How many buses can use the same charger, and what the utilisation rate is? For example, charger costs can be shared between the buses that use it.
- How much is the annual mileage? For example, an electric bus saves more expenses compared to a diesel bus the more you drive it.
- What is the line terminus time? For example, optimal terminus times minimise the indirect costs for additional equipment and staff.
- How much does the terminal stop time shorten during peak hours?
- How long is the route? This information affects the battery dimensioning.

With these calculations, line 2 was identified to be well suited for electric buses. The line is relatively slow and contains a lot of traffic lights. Electric buses are very suitable for urban traffic on routes with lots of stops and traffic lights, allowing energy efficiency compared to diesel buses.

The selection of the charging type in the procurement affects the selected line. The study by Markkula and Vilppo states that charging at the terminus is the best option because then the battery size may be small [44]. If buses were to be charged only in the depot, the passenger space would be reduced because the battery needs to be bigger and thus requires space. The charging method selection was also in favour of line 2, which is suitable for an electric bus line due to its Pyynikintori terminal. Pyynikintori has several line terminuses, which allows the charging station to be used jointly on several bus lines. Using the charger on more than one line would increase the system's profitability. It was also considered whether the terminal has enough time to charge when choosing a line.

During the monitoring period, line 2 experienced minor route changes as the construction of a tram site progressed in the centre of Tampere. Figure 3 illustrates how the route has changed since 2018.

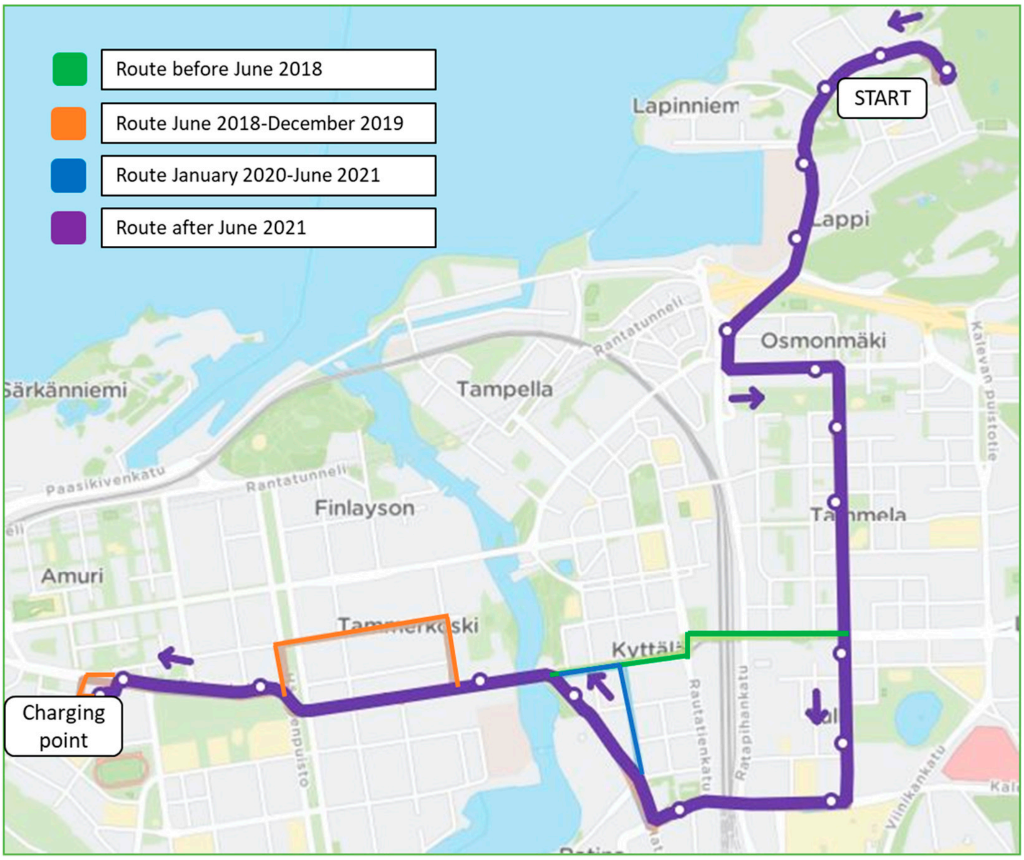


Figure 3. Line 2 changes due to the tram site.

During the procurement process, many issues related to the procurement method and the technology to be procured had to be resolved, confirming earlier findings that the operation of electric buses requires more planning than the operation of conventional buses [10]. For example, the choice of procurement method was already the subject of debate. The decision on the open procedure was questioned. The experience of Tampere concerning electric bus systems was still limited, which raised many additional questions during the acquisition. In this respect, the conciliation procedure would have been more forgiving. The market dialogue aimed to identify available solutions and meet the city's needs. The key issue for the procurement was whether the electric buses and chargers were to be purchased separately or together. The city ended up with a single-supplier model because it was perceived to simplify procurement, which already had sufficient uncertainties. This model could avoid possible disagreements between the bus and charger supplier.

Already in 2019, the buses had travelled 600,000 km. Theoretically, the mileage should have been 800,000 km. The lost driving time is due to, e.g., traffic accidents in cramped urban traffic that led to sheet metal crashes. According to Nysse's (Tampere regional public transport organization) own customer feedback survey on using the electric buses, the passengers have given positive feedback. The electric buses have a low noise level, and they are easily accessible because of low-floor vehicles, three wide doors and no steps on the aisle. The only negative feedback has been a large number of rear-facing seats in low-floor city buses.

The development of a sustainable public transport system requires a shift to emission-free bus transport, the development of smooth travel chains and new mobility services, and an overall improvement in service level to increase the modal share of public transport in line with the target set. Targets in the number of outsourced transport services using low emission fuel sources (bus and tramway line kilometres) are set 35% (2025) and 100% (2030). More than 700 tonnes of CO_2 emissions have been saved during the pilot. This is a conservative estimate because the saved CO_2 emissions had to be partially extrapolated to the monitoring time due to data interruptions. In spring 2021, Tampere started a tender for two different bus lines. The requirement was that buses must comply with the clean vehicles Directive (EU 2019/1161). The selected operator implements the requirements with an electric bus system. During spring 2022, there will be 26 new electric buses when the winning operator brings its buses into service.

4.2. Monitoring and Estimation of Energy Consumption

During the monitoring period between 2019 and the end of August 2021, the four electric buses travelled approximately 500,000 kilometres using an average of 1.43 kWh/km electricity. Figure 4 shows seasonal variation of energy efficiency between 2019–2021 in monthly intervals. However, it has to be taken into account that cooling systems use electricity during summer and heating during winter. These electricity consumptions could not be separated in our monitoring setup.

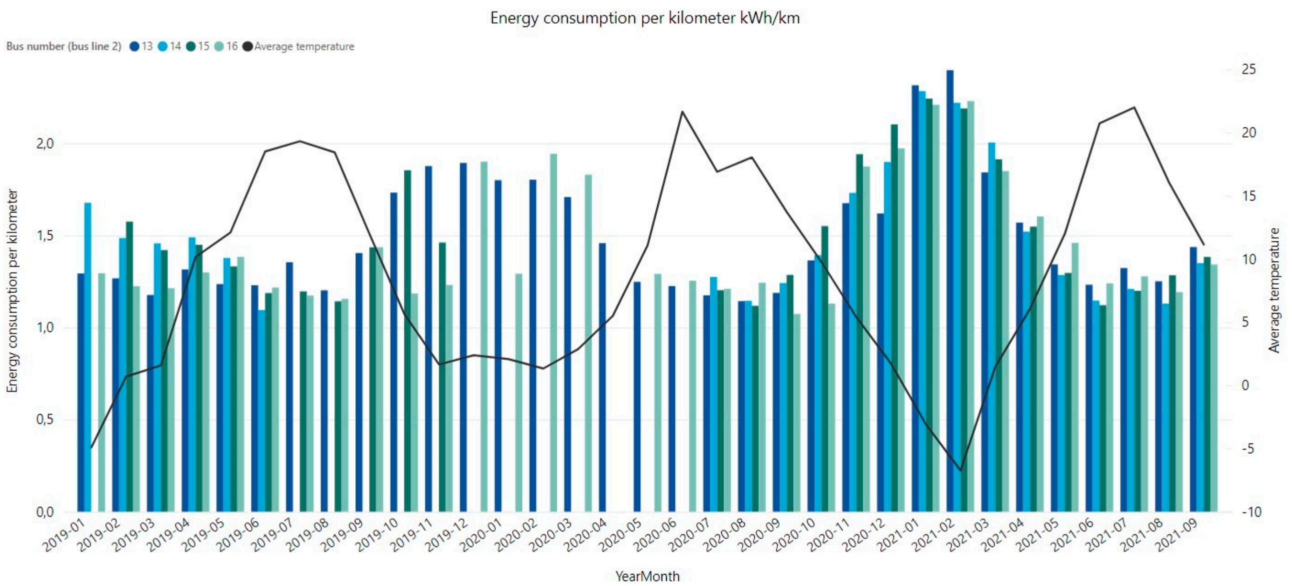
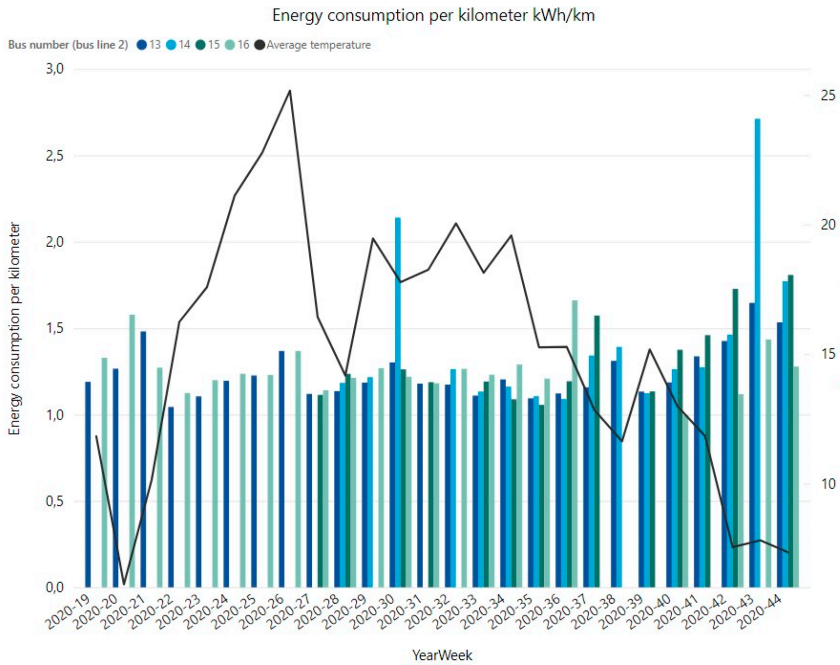


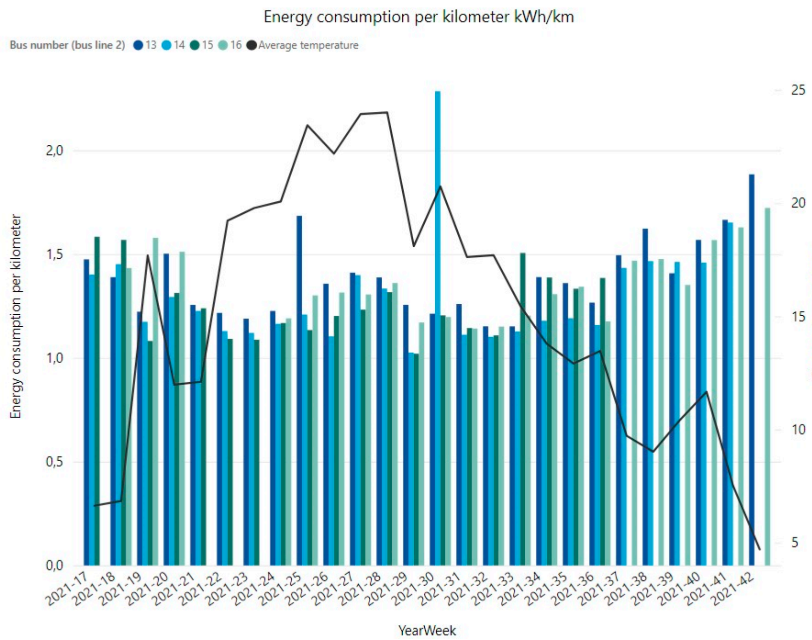
Figure 4. Example of created monitoring dashboards: energy consumption. Disclaimer: The comma is used as a decimal separator instead of a dot because the version of Power BI used in the visualization followed the grammar rules of the Finnish language.

The monitoring setup experienced fewer problems during the last two years. Thus, these years are more closely analysed. Figures 5 and 6 show summer, and Figures 7 and 8 wintertime, separately divided into weekly intervals. Summer is defined as the months between May and October. Respectively, winter is defined by the months between November and April.



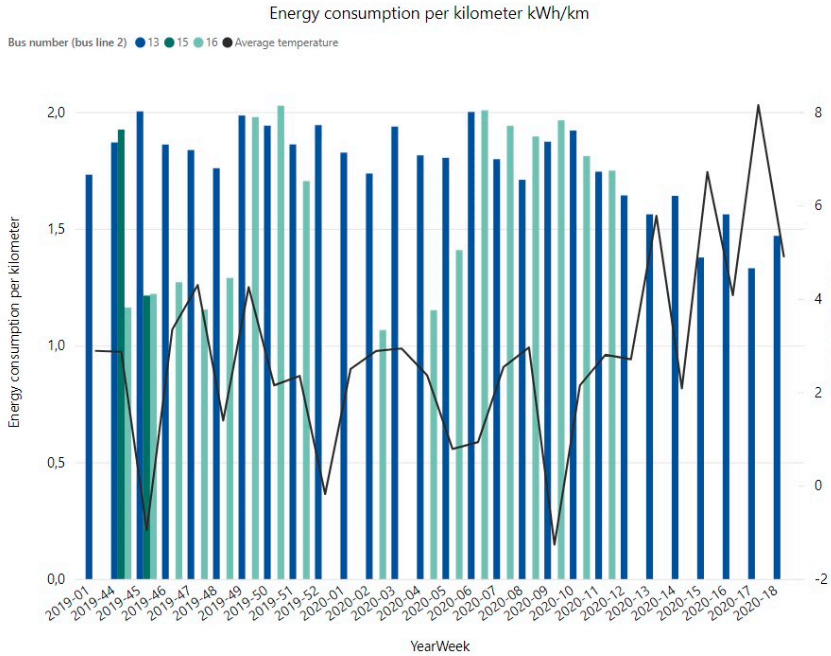
Energy Eff	Distance traveled	YearWeek	YearMonth	Outside temperature
2,5421	45,16	2020-43	2020-10	8,26
1,6931	942,58	2020-44	2020-10	7,35
1,5030	3 330,38	2020-42	2020-10	7,55
1,4574	1 240,40	2020-20	2020-05	6,12
1,3748	2 651,64	2020-38	2020-09	11,86
1,3679	2 173,13	2020-26	2020-06	25,16
1,3602	1 887,00	2020-30	2020-07	17,77
1,3553	3 090,00	2020-41	2020-10	11,91
1,3114	1 429,37	2020-21	2020-05	10,14
1,2877	2 735,91	2020-37	2020-09	12,89
1,2854	1 626,24	2020-40	2020-09	13,32
1,2765	1 709,05	2020-40	2020-10	12,68
1,2326	2 770,19	2020-32	2020-08	20,42
1,2320	915,83	2020-19	2020-05	11,82
1,2273	2 436,33	2020-25	2020-06	22,77
1,2255	574,72	2020-36	2020-08	15,11
1,2227	3 648,95	2020-29	2020-07	19,59
1,2172	1 887,59	2020-24	2020-06	21,11
1,1899	1 859,44	2020-31	2020-07	17,82
1,1841	4 177,51	2020-28	2020-07	14,17
1,1786	680,38	2020-27	2020-06	17,79
1,1701	3 936,72	2020-34	2020-08	19,58
1,1590	3 762,97	2020-33	2020-08	18,14
1,1519	1 776,68	2020-23	2020-06	17,58
1,1392	443,73	2020-31	2020-08	19,75
1,1290	3 310,81	2020-39	2020-09	15,18
1,1187	3 988,21	2020-35	2020-08	15,26
1,1155	1 380,22	2020-22	2020-05	16,24
1,1124	2 388,63	2020-36	2020-09	15,32
1,1106	1 905,23	2020-27	2020-07	15,96
		2020-18	2020-05	16,41
1,2450	**64 705,00**			**15,81**

Figure 5. Energy efficiency and outside temperature per week during 1 May 2020–31 October 2020. Disclaimer: The comma is used as a decimal separator instead of a dot because the version of Power BI used in the visualization followed the grammar rules of the Finnish language.



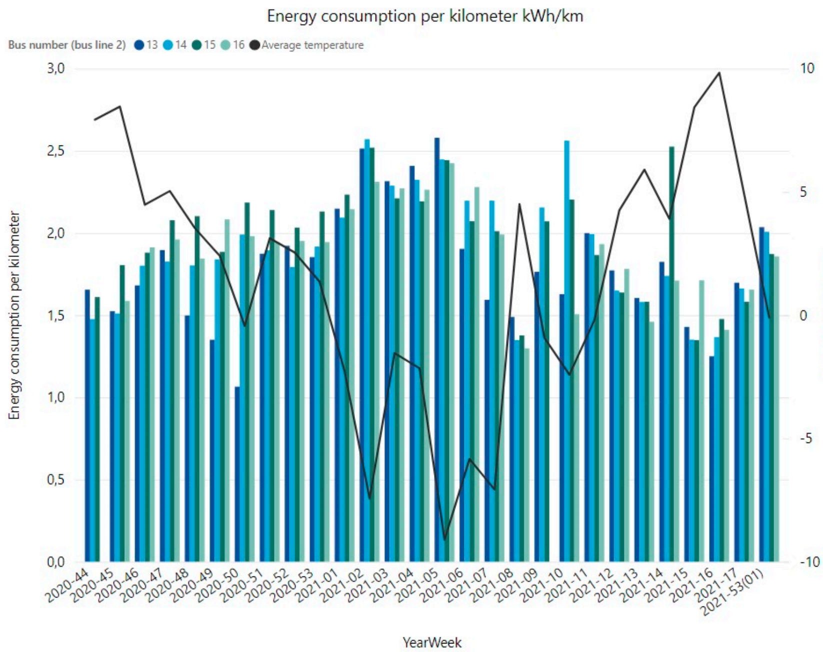
Energy Eff	Distance traveled	YearWeek	YearMonth	Outside temperature
1,7974	2 035,60	2021-42	2021-10	4,76
1,6481	2 850,27	2021-41	2021-10	7,51
1,5339	2 967,90	2021-40	2021-10	11,67
1,5302	3 031,62	2021-38	2021-09	9,10
1,4844	2 622,46	2021-37	2021-09	9,81
1,4805	847,15	2021-17	2021-05	6,99
1,4781	3 370,11	2021-18	2021-05	6,85
1,4145	1 573,22	2021-39	2021-10	10,57
1,3844	1 481,91	2021-39	2021-09	10,27
1,3650	3 948,14	2021-20	2021-05	11,98
1,3584	2 730,13	2021-35	2021-09	11,53
1,3544	4 115,00	2021-28	2021-07	24,01
1,3163	3 397,09	2021-27	2021-07	23,94
1,3152	4 627,91	2021-34	2021-08	13,79
1,2686	2 697,06	2021-26	2021-07	23,00
1,2511	4 506,61	2021-36	2021-09	13,47
1,2407	3 007,87	2021-25	2021-06	23,44
1,2401	3 333,53	2021-21	2021-05	12,11
1,2322	3 791,26	2021-33	2021-08	15,47
1,2299	2 863,91	2021-30	2021-07	21,10
1,2117	1 227,99	2021-35	2021-08	16,39
1,1884	4 120,15	2021-24	2021-06	20,07
1,1834	3 849,89	2021-19	2021-05	17,69
1,1683	1 584,16	2021-26	2021-06	20,79
1,1656	3 574,84	2021-31	2021-08	17,62
1,1649	413,41	2021-22	2021-05	13,74
1,1470	3 917,99	2021-29	2021-07	18,10
1,1360	3 155,81	2021-22	2021-06	19,96
1,1335	3 553,36	2021-23	2021-06	19,78
1,1227	3 637,81	2021-32	2021-08	17,70
1,0120	334,97	2021-30	2021-08	17,47
		2021-43	2021-10	14,88
1,3039	**89 169,13**			**15,78**

Figure 6. Energy efficiency and outside temperature per week during 1 May 2021–31 October 2021. Disclaimer: The comma is used as a decimal separator instead of a dot because the version of Power BI used in the visualization followed the grammar rules of the Finnish language.



Energy Eff	Distance traveled	YearWeek	YearMonth	Outside temperature
2,0295	984,47	2019-52	2019-12	0,25
2,0062	1 312,95	2020-06	2020-02	0,93
1,9899	2 026,92	2019-50	2019-12	2,15
1,9844	289,81	2020-09	2020-03	1,42
1,9797	1 394,12	2019-49	2019-12	4,25
1,9359	219,54	2020-03	2020-01	2,94
1,9099	2 365,61	2020-09	2020-02	-1,64
1,8689	2 720,52	2020-07	2020-02	2,54
1,8629	1 813,85	2020-10	2020-03	2,15
1,8248	897,40	2020-01	2020-01	2,50
1,8088	1 957,38	2019-51	2019-12	2,35
1,7897	2 411,24	2020-08	2020-02	2,96
1,7631	386,03	2020-14	2020-03	0,25
1,7457	1 849,09	2020-11	2020-03	2,80
1,7314	1 043,50	2020-02	2020-01	2,88
1,7303	398,09	2019-01	2019-12	3,52
1,6559	1 572,80	2020-04	2020-01	2,37
1,6474	1 346,36	2020-12	2020-03	3,04
1,6457	1 227,87	2020-05	2020-01	0,51
1,5933	988,18	2020-14	2020-04	2,83
1,5715	2 477,76	2019-46	2019-11	3,34
1,5691	1 353,69	2019-44	2019-11	2,87
1,5637	861,70	2019-47	2019-11	4,30
1,5618	1 189,13	2020-16	2020-04	4,08
1,5611	1 106,81	2020-13	2020-03	5,89
1,4952	3 030,51	2019-45	2019-11	-0,95
1,4700	816,79	2020-18	2020-04	4,91
1,4679	1 759,59	2019-48	2019-11	1,57
1,4009	198,87	2019-48	2019-12	-0,25
1,3771	1 303,71	2020-15	2020-04	6,71
1,3312	1 243,82	2020-17	2020-04	8,15
		2020-05	2020-02	17,19
1,7091	**42 548,11**			**2,47**

Figure 7. Energy efficiency and outside temperature per week during 1 November 2019–30 April 2020. Disclaimer: The comma is used as a decimal separator instead of a dot because the version of Power BI used in the visualization followed the grammar rules of the Finnish language.



Energy Eff	Distance traveled	YearWeek	YearMonth	Outside temperature
2,4620	4 080,85	2021-02	2021-01	-7,44
2,4527	3 607,52	2021-05	2021-02	-9,11
2,3305	2 238,70	2021-10	2021-03	-2,42
2,2877	4 230,76	2021-04	2021-01	-2,16
2,2710	4 531,80	2021-03	2021-01	-1,54
2,1709	2 712,32	2021-06	2021-02	-5,83
2,1555	3 563,59	2021-01	2021-01	-2,28
2,1052	1 365,34	2021-09	2021-03	-0,41
2,0313	2 289,59	2021-07	2021-02	-7,07
2,0249	382,15	2020-49	2020-11	1,51
1,9694	4 165,50	2020-51	2020-12	3,12
1,9482	1 740,82	2021-53(01)	2021-01	-0,10
1,9478	2 655,28	2020-53	2020-12	1,35
1,9428	3 759,81	2021-11	2021-03	-0,20
1,9345	4 297,60	2020-47	2020-11	5,03
1,9330	3 404,62	2020-52	2020-12	2,54
1,8592	3 757,65	2020-48	2020-11	3,53
1,8566	2 984,28	2020-49	2020-12	2,51
1,8464	4 714,75	2020-50	2020-12	-0,44
1,8082	4 275,38	2020-46	2020-11	4,48
1,7676	2 487,15	2021-14	2021-04	3,91
1,7060	4 054,59	2021-12	2021-03	4,26
1,6898	1 582,71	2021-13	2021-03	6,82
1,6465	3 489,48	2021-17	2021-04	4,88
1,6039	3 979,35	2020-45	2020-11	8,46
1,5839	506,79	2020-44	2020-11	7,93
1,4894	2 252,52	2021-13	2021-04	5,23
1,3979	2 688,80	2021-15	2021-04	8,42
1,3689	1 403,99	2021-16	2021-04	9,83
1,3571	267,41	2021-08	2021-02	4,50
1,9457	**87 471,10**			**1,13**

Figure 8. Energy efficiency and outside temperature per week during 1 November 2020–30 April 2021. Disclaimer: The comma is used as a decimal separator instead of a dot because the version of Power BI used in the visualization followed the grammar rules of the Finnish language.

The findings show that the energy consumption was 1.24 kWh/km during summer 2020 and 1.30 kWh/km during summer 2021. Then again, the energy consumption was 1.71 kWh/km during winter 2020 and 1.95 kWh/km during winter 2021.

The results of this study inform traffic planners on how electric buses perform in different environmental conditions. Several factors influence the energy consumption of electric city buses. The design considerations such as the total mass of the bus and the regeneration rate can significantly affect the energy efficiency. Several studies have been made where the driving range of different structure selection have been analysed by making simulation or analysing measured data [10,45,46]. This investigation focuses on the effect of environmental factors since the monitored buses are completely similar. In cold climatic zones, the temperature changes the most energy consumption. Still, the number of passengers, road topography, traffic congestion, driving style, and surface condition contribute to it, as previous studies have shown [16,20,36].

The previous results dealt with daily averages. It is necessary to analyse each driving from Pyynikintori to Rauhaniemi individually to obtain more detailed information on the effect of weather phenomena on consumption. Since the elevation variations along the route are about 28 m, the directions are analysed separately. Measurements from January 2019 to August 2021 have been selected for the study. There have been some changes to the route, but they are so minor that their effect is negligible. The lengths of the routes have ranged from 8.8 km to 10.3 km. The analyses have been performed only for working day hours from 6:30 to 22:30 and on a route where the doors have been open for more than half a minute to obtain comparable results.

Figure 9 shows electrical energy consumption as a function of temperature so that each blue dots represent one drive between the start and end station. Since 2019, it has been possible for the operators to choose between diesel fuel and electricity for heating the battery and the interior. The measurements show that most drivers had opted for fuel heating. This option was removed from 2020 onwards, and the fuel heater was controlled automatically; it was activated only when the ambient temperature was below –15 °C. This can be clearly seen from the figure. The figure also has a polynomial curve fit to data, which have been carried out in two separate cases due to the diesel heating. Below 0 °C, the fitting is carried out to temperature data between −15 and 10 °C. At temperatures above zero degrees, a fitting was made to those values. The energy consumption (EC) is shown in Equation (1), where T is the temperature in degrees Celsius.

$$EC = \begin{cases} 5.4 \times 10^{-5}T^3 - 2.7 \times 10^{-4}T^2 - 0.05T + 1.6, & T \geq 0\,^\circ C \\ -0.04T + 1.6, & T < 0\,^\circ C \end{cases} \quad (1)$$

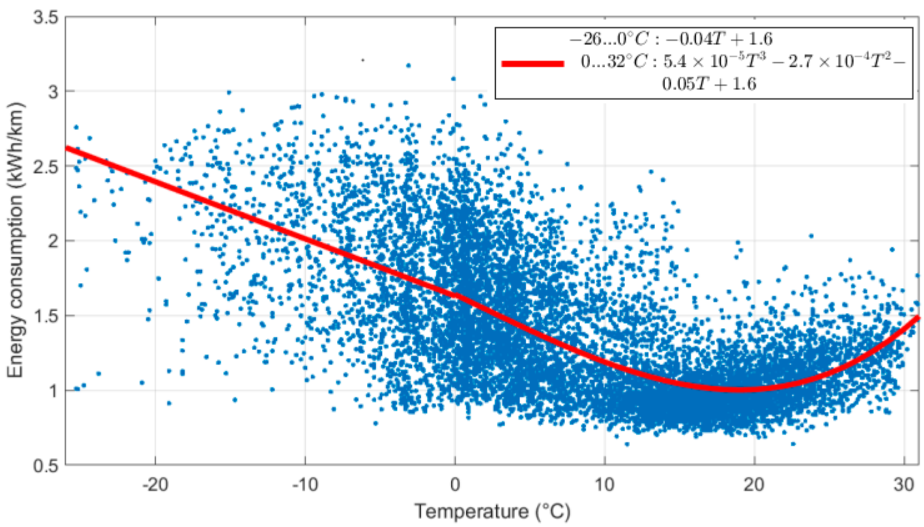


Figure 9. Energy consumption as a function of temperature (blue dots—samples; red line—polynomial curve fit).

The graph shows that the average energy consumption increased by about 0.4 kWh when the temperature decreased to 10 °C. Air conditioning increases consumption when the temperature is above 15 degrees. Its effect is approximately equivalent to an increase in consumption at temperatures below zero.

Two outlier groups are interesting: (1) Although there is considerable frost, there is small consumption, and (2) high consumption near zero degrees. A common feature of the first case is the short duration when doors are open, meaning few passengers and little heat escaping from the doors. There might be several reasons for the second group: snow, slush or slippery road. In any case, they have the doors open for a long time, indicating a lot of passengers.

Table 1 shows energy consumption (kWh/km) for different cases for 2019 and 2020–2021 separately due to the change in the heating mentioned above. The data is the same as in Figure 9 except that the cumulative passenger entry and exit time shall be at least one minute. There are some high values for 2019 since the winter was rather cold and snowy. The highest six values occurred when the temperature was between −1 and 5 °C. This reflects the fact that snowy weather, particularly snowmelt, increases consumption significantly. Winter 2020 was warm and had hardly any snow, but 2021 had cold and snowy winter. The median energy consumption was 0.8 kWh/km greater when the temperature was below zero than over zero. Again, there were some high consumptions near zero degrees, which can be observed from the figure. The median difference between driving the route when the snow was melting and without melting was 0.2 kWh/km. The distribution of melting cases was twofold: either it had little effect, or the consumption increased greatly. Understandably, a small melt has little effect, but if the vehicle is driven in slush ice, consumption increase considerably.

Table 1. Energy consumption (kWh/km) for specific conditions.

	2019				2020–2021			
	Samples	**Median**	**Mean**	**Max.**	**Samples**	**Median**	**Mean**	**Max.**
Doors open 1–3 min	3354	1.1	1.2	3.1	7592	1.2	1.3	3.0
Doors open > 3 min	2839	1.2	1.3	3.5	1536	1.4	1.5	3.2
Temperature ≥ 0 °C	4638	1.1	1.3	3.5	7282	1.1	1.2	3.0
Temperature < 0 °C	1555	1.2	1.4	3.5	1846	1.9	1.9	3.2
Snowing > 0 cm/h	551	1.2	1.4	3.0	539	1.8	1.8	3.0
Snowing > 1 cm/h	239	1.2	1.4	2.8	229	1.9	1.9	2.9
Snow melt or sublimation	1220	1.2	1.3	3.5	1260	1.7	1.7	3.1
Temperature −1–10 °C without snow melt	1602	1.2	1.4	3.4	2158	1.4	1.5	3.0
Temperature −1–10 °C and snow melt	877	1.2	1.3	3.5	977	1.6	1.6	3.1

The results show that the weather and climate affect the operation of buses and the entire electric bus system. Four electric buses travelled approximately 500,000 kilometres (2019–2021) using an average of 1.43 kWh/km electricity. However, this number also includes the energy use by cooling systems during summer and heating during winter, as they could not be separated in the monitoring setup. The average energy consumption during thermal winter was 2.1 kWh/km and 1.2 kWh/km during thermal summer. Thermal winter starts when the average temperature is below 0 degrees Celsius at least five days in a row. Thermal summer starts when the temperature is over +10 degrees Celsius at least five days in a row. In Tampere, the thermal winter was 7 December 2020–22 March 2021, and thermal summer was 10 May 2021–14 September 2021.

4.3. Experiences in Operating and Charging Electric Buses

The electric motor does not generate waste heat the same way as a diesel motor, and separate heating must be provided. When electric buses started to operate in Tampere, the heating system worked with diesel fuel. The heating system was changed in winter

2019 to an electricity-based system where the water circulation system is electrically heated. In the beginning, a bus driver could select if the electric heating is used instead of a fuel heater. It was noticed that drivers tended to select the fuel heater, as they wanted to avoid charging as it was difficult. Therefore, the operation was changed so that the electric heating is the default, and the fuel heater activates if the outside temperature decreases under -15 degrees Celsius. The effect can be seen when comparing the winter energy consumption between 2020 and 2021.

The study finds that the effect of cooling is minor compared to the effect of heating energy needs. The data includes two different periods in which the buses were using different control strategies for indoor heating. The second winter period shows the increase in electrical energy consumption when using a full electric indoor heating instead of using an auxiliary fuel heater for heating when a heat pump cannot produce enough heating power. When considering local emissions and total greenhouse gas emissions of an electric bus system, one option to minimise the emissions is to go for full electric heating. Still, the penalty in cold climates is the increased battery energy consumption at very low temperatures, which needs to be taken into account in the electric bus charging design—either the battery capacities need to be increased to be able to handle the additional consumption, or opportunity charging needs to be arranged to be able to charge the buses more often.

A more detailed analysis of energy consumption would have required data that was not accessible because there was no mention of ownership or access to the data in the model leasing agreement. This must be considered in future agreements in other areas than e-mobility.

Another area that could use detailed data is the passenger number and its effect on energy consumption. Currently, only passengers boarding the bus can be entered into the information system. Therefore, the exact number of passengers is not known. The city of Tampere has carried out pilots to monitor the number of passengers to monitor, improve and optimise the occupancy rate, but this is still a clear area for development and research; how many passengers there are and how their number affects energy consumption. The graphs (Figures 10 and 11) show the number of passengers per hour made by one bus. Winter weather is not attractive for cycling or walking. Passenger number is smaller during summertime compared to winter. The bus runs a round trip from the departure stop to the charging station (one end) and back during the hour. It can be estimated that the passenger number in the bus simultaneously during peak hours is ~50.

The energy consumption of electric buses as a whole has been lower than expected, but the differences per driver have been surprisingly large. For the project, it was impossible to monitor driver-specific energy consumption more accurately since it would have required an act on co-operation [47].

The study also reveals that when setting up and operating charging systems with automated charging devices (pantographs), the effects of the weather must be considered when selecting and preparing the location of the charging point. The buses were charged with a bus-mounted pantograph, where an automated charging connector rises from the bus roof to connect with a receptacle mounted on a charging mast or pole (Figure 12). This connection has some tolerances for misalignment, but snow build-up on the driving tracks during winter has shown in practice that these tolerances are not enough to maintain a reliable connection in all weather conditions without additional measures.

Positioning the bus under the charging system pantograph was a difficult task in the beginning since the bus needed to be in an exact correct spot to initiate the charging. Therefore, paint markers on the curb were used. The bus's front door was aligned with the markers when the bus was in a correct position (Figure 13). Another challenge was the alignment of the bus lateral distance from the kerb.

A defrost system was built at the Pyynikki charging point to prevent a hard snow ridge from building on the charging point driving tracks. The defrosting system caused decreasing soil bearing capacity, and buses driving to the same spot for charging caused a depression to the charging area, causing problems in the charging connection. A heated concrete foundation was built, and the area was paved again with new asphalt. There have been no problems with durability since the latest repair.

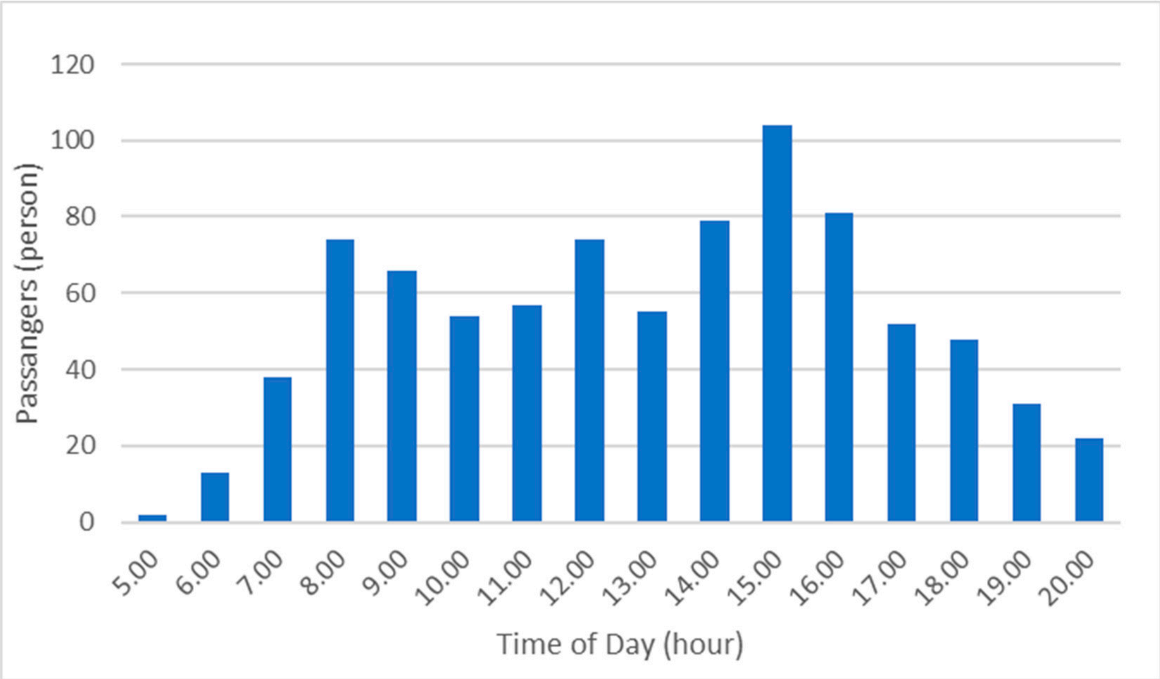


Figure 10. Passengers on one bus shift (13 February 2020).

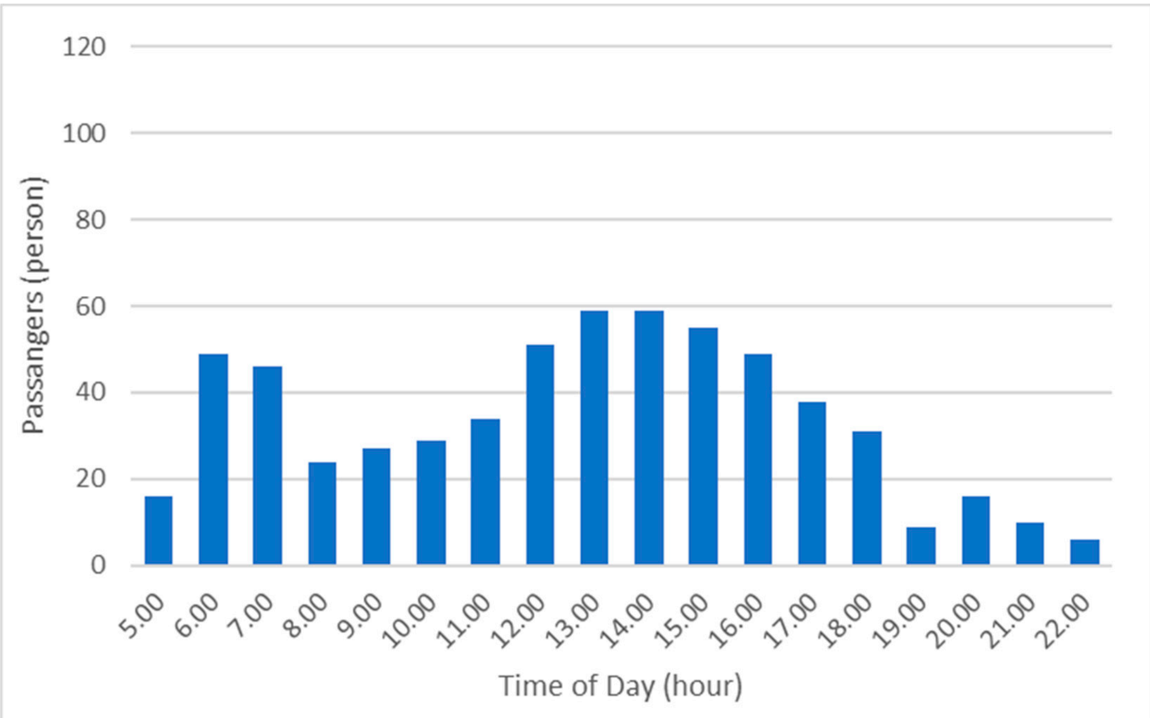


Figure 11. Passengers on one bus shift (11 July 2019).

Figure 12. Heated foundation for the charging point to remove snow build-up on driving tracks.

Figure 13. Paint markers on the kerb to position the bus for charging.

In addition to the equipment that affects the operation of the electric bus system, people and the operation of electric buses also notice the great importance of the way drivers drive, for example, in energy consumption, which raises the importance of training the drivers.

Operating electric buses is generally different from operating diesel or hybrid buses. There was some training included in the contract with Solaris, but common thought amongst drivers has been that there should have been more operator training. The charging was perceived to be difficult for drivers, and the driving style affected the electricity consumption greatly. Driver assistance tools could be one solution to help drivers better operate electric buses [48].

5. Conclusions

The data shows the increased energy consumption of electric buses in cold climatic conditions. During thermal winter, the average energy consumption was 2.1 kWh/km and 1.2 kWh/km during thermal summer. Thermal winter starts when the average temperature is below 0 degrees Celsius at least five days in a row. Thermal summer starts when the temperature is over +10 degrees Celsius at least five days in a row. When comparing the best-case energy consumption in summer, with energy consumption of roughly 1.1 kWh/km with the hot summer weeks of around 1.35 kWh/km and cold winter weeks with the highest energy consumption of almost 2.5 kWh/km, one can see that the effect of cooling is minor compared to the effect of heating energy needs.

When using a fuel heater, the energy consumption from the battery can be reduced, with the best results being roughly 1.35 kWh/km. This was also indicated by the operators' behaviour when they could prioritise the diesel heater to avoid charging. However, using a fuel heater comes with the cost of local emissions, even though the fuel would be from sustainable sources. When using electric heating, local emissions can be minimised. Even with diesel heating during colder months, the greatly increased energy consumption from the traction battery needs to be taken into account in the charging design—either the battery capacities need to be increased to be able to handle the additional consumption, or opportunity charging needs to be arranged to be able to charge the buses more often. Driving in the heavy slush ice, in particular, increases consumption considerably.

The comments from the interviews highlight the systemic nature of the electrification of transport. The design of an electric bus system, especially in cold climate conditions, needs to address appropriate energy transfer to the buses, without affecting the operation, in all conditions. The system needs to have enough safety margins in case of faults and for additional energy consumption in harsh weather conditions. Charging equipment and locations need to withstand the continuous loading of soil on same positions and maintain the potentially needed opportunity charging systems within their operating tolerances. Finally, appropriate training for operators, maintenance, and all relevant personnel can help avoid disturbances caused by charging and excessive energy consumption by driving style.

The motivation for this test was to determine whether the electrification of public transport helps achieve the carbon neutrality goal of Tampere. This goal was met, but the test raised several technical issues, such as the energy consumption of different devices and the impact of driving styles. The depth of analysis was limited because the test project was not granted access to the leasing bus internal data collection system. In addition, some issues during the analysis phase were caused by the synchronisation of time series data from different sources, which should also be taken care of when setting up a data collection system.

Promoting alternative propulsion for transport and procuring an electric bus system are ways to achieve the city's climate goals. In addition to meeting the emission targets, there is a desire to try new promising technology in public transport, which will lead to cost savings in the longer term. The acquisition was also based on the goal of making the electric bus line an innovation platform for intelligent transport, which can be used to test and put into practice products and services related to intelligent transport. On the operational side, the experience was gained, and an overview of operations was obtained in winter conditions. From the point of view of innovation and information, leasing buses is not ideal unless the contract ensures that the collected data can be utilised with sufficient precision for the subscriber. Unfortunately, the agreement did not take a sufficient position on data ownership. There was no agreement on data collection, which prevented a more detailed analysis of energy consumption. With a view to future agreements, data ownership must be considered, and transparency of operations is important for development and scientific studies.

Further research could collect more data to conduct a more thorough operational analysis using the charger and charging process data, including the vehicle alignment to the charging point. For example, the number of unsuccessful charging attempts could have pointed out areas of improvement in the charging process or training. The effect of drivers' driving style on energy consumption is an interesting area for study, but such research must take into account GDPR and the required anonymisation of data. Tampere collects a lot of data related to traffic and distributes it as open data [49]. Combining this data with more accurate data collected from buses creates the basis for new studies and the ability to find correlations between conditions and different parameters.

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Institutional Review Board Statement: Not applicable.

Informed Consent Statement: The interviewees have been explained the purpose of the interview and the study, and they have given their consent to the interview. Participation in this research project have been voluntary and interviewees did not receive any payments for participating in this research interview. Sensitive information was not discussed in the interviews. Interviews were conducted by teams discussions, and no audio or video was recorded, only written notes were collected.

Data Availability Statement: The city of Tampere provides the following data publicly available for reuse: the hourly energy consumption and distance traveled of the three electric buses and one hybrid bus. The data, provided in an Excel format, and the data's metadata can be downloaded from the IDA research data storage service, which is organised by the Finnish Ministry of Education and Culture and maintained by CSC (IT Center for Science Ltd.). The dataset's metadata can be downloaded as a JSON file. Two datasets are available in the IDA service: (1) *Ebus distance data*, which shows how many kilometres the four electric city buses have travelled in Tampere, is available: https://etsin.fairdata.fi/dataset/199dff1c-389d-4069-a55d-c2d9e2379a2d (accessed on 3 March 2022). The columns of the 4.68 MB Excel file are: busId, nodeId, variable, unit, date, time, number start, number (end), actual, updated_timestamp. (2) *Ebus electricity consumption data*, which shows the electrical energy consumption of the four electric buses in Tampere, is available: https://etsin.fairdata.fi/dataset/cbea812a-9093-44c6-8cc9-041770b41c7d (accessed on 3 March 2022). The columns of the 1.93 MB Excel file are: date, time, busId, nodeId, SUM, Updated_date. The datasets are available under the creative commons license (CC BY 4.0), which allows the user to (1) Share—copy and redistribute the material in any medium or format and (2) Adapt—remix, transform, and build upon the material for any purpose, even commercially, provided that the dataset is given appropriate credit and any changes are indicated.

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