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Exploring the profitability of using electric bus fleets for transport and power grid services

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Abstract

Electric buses (E-buses) are increasingly replacing internal combustion powered bus fleets. They can further function as distributed energy storage units. We investigate the feasibility of the novel “Bus-to-Grid” (B2G) or “E-Buses as Power Storage” (EBaPS) concept, which allows E-buses to provide transportation as well as power-grid services. By aggregating the electrified bus fleets into Virtual Power Plants and discharging the energy to the grid, a bus operator can provide grid services and open up a secondary revenue source in addition to fareboxes. We discuss two contracts the bus operator can arrange with the grid. The first one is “Sale by Market Price (SbMP)”, presuming that the buses can discharge and sell the energy at real-time market prices. The second one is “Frequency Control Reserve (FCR)”, in which the buses discharge on immediate requests of the grid. We formulate the two contracts and their associated fleet allocation problems as two non-linear optimization problems maximizing the operator’s profit. Optimal bus charging, discharging, and dispatching plans are solved on an aggregate level for strategic planning allowing scalability to large fleet sizes. The profitability of the contracts is illustrated based on the schedule and demand of a real bus line and observed time-of-day dependent price variations of the energy market.

Keywords: Bus fleet electrification, Bus to Grid, Fleet allocation, Vehicle to Grid, Virtual Power Plant, Bus operator profitability

1 Introduction

The primary role of greenhouse gas emissions in climate change has become one of the world’s most pressing challenges. According to the latest greenhouse gas emissions statistics, the transport sector accounts for 27% of the total emissions (IEA, 2021a). In response, many countries focus on developing greener transportation. They have been implementing policies to encourage people to purchase electric vehicles (EVs) and building up the charging infrastructure. In many countries, ambitious EV sales targets are playing an important role to

reach ambitious CO₂ emissions standards (IEA, 2021b). Owing to these, the overall EV stock reached 10 million by 2020 and 82000 new E-buses were registered globally (IEA, 2021c). The considerable amount of costs for purchasing and maintaining an E-bus fleet have been obstacles for an even wider deployment. However, with maturing of the technology E-buses are becoming also financially more attractive and their share is expected to increase significantly in the near future. At the same time, additional financial incentives could further encourage a faster transition to the much-needed replacement of - often old - internal combustion engine buses with environmentally friendlier E-buses. This motivates our study.

So far, a large body of studies have cast attention on the planning and operation aspects of E-buses, but limit themselves to a discussion of bus charging and dispatching problems. In this research, we suggest that E-buses could lead to further service implications if they are used in a dual role. We suggest that vehicle-to-grid (V2G) and virtual power plant (VPP) technologies can open up a new source of revenue for bus operators if they decide to electrify their bus services.

The V2G concept enables EVs to engage in power grid services. EVs communicate with the power grid to either sell or purchase electricity (Kempton and Tomić, 2005; Taiebat and Xu, 2019). V2G technology, therefore, enables EVs to function as a distributed and mobile energy storage unit that can serve as an external demand supplier for the power grid. As the subsequent literature review will show most of the discussion is on using car fleets, but we note that by now there are also initial trials of using these for grid services. In London bus-to-grid-technology has been trialed since 2021 and since recently the usage of schoolbuses for grid services is on trial in Ontario, Canada (Smart Energy International, 2021; Electric Autonomy Canada, 2022). Details of the business models for these trials are not reported.

VPPs integrate several types of power sources, such as renewable energy, power storage, and flexible power consumers, in order to monitor, forecast, optimize, and trade their power (Dielmann and van der Velden, 2003; Zajc et al. 2019). By integrating renewable energy into the market, VPPs help to bridge the gap between energy demand and supply for the grid and customers. They enable the grid to stabilize the power supply over time and in turn the market price of energy. Besides, VPPs that base their energy on renewable energies are hoped to replace the power supply based on fossil fuels. A major challenge of renewable energies is their weather-dependent power generation so backup systems are required. Small plants that conventionally cannot provide stable services due to the lack of capacity for power exchanges can also trade with large central power plants by joining VPPs. Therefore, EVs connected to the grid by V2G technology can play the role of such “small power plants” and join the energy market within VPP platforms as discussed by Kahlen et al. (2018). To further highlight the potential additional benefits of VPPs, we note that smart grids and digital investments account for around 40% of total grid investment in “Net Zero Emissions” programs in the last decade (IEA, 2021d).

In this research, a VPP scheme with the integration of E-buses as shown in Fig. 1 is proposed. We suggest “E-Buses as Power Storage” (EBaPS), meaning that E-buses can be part of the solution to store energy and

supply it to the grid at other times of the day. Though the scale of bus fleets is smaller than that of private vehicles, we propose that their larger batteries and the higher feasibility to be centrally controlled could mean that E-buses can be reliable contributors to the power grid services through this VPP. In this paper, we mainly model the interactions between VPPs, the bus operator of the electrified fleets, and the passengers, with a focus on the transportation systems' side.

We will discuss two ways in which E-buses could be integrated into the energy supply network (and possibly a combination of the two). The first one is “Sale by Market Price (SbMP)”. Here the bus operator can receive revenues by discharging the bus and selling energy to the grid given the highly dynamic market prices. That is, the bus operator can charge at times when energy prices are low and sell at times of day when energy prices are high. This could hence be a win-win situation for the bus operator and the energy provider. However, in particular if the fleet size is limited, potentially passengers might be on the losing end of this if the energy market is so lucrative that selling energy is more profitable than using buses for the prime role. We hence explore in this research the potential trade-offs of an SbMP contract with passenger service quality.

The second contract is for buses to support “Frequency Control Reserve (FCR)”. FCR ensures that the power supply and demand are constantly balanced by supplying or consuming extra energy when there is a gap or an excess demand respectively (Iacobucci et al., 2021). Therefore, in order to ensure that potential power shortages can be compensated in time, in an FCR contract the bus fleet needs to set aside a certain number of buses to be ready to discharge at any time. This, “buses as insurance”, scheme might have implications for service provision in peak hours when potentially all buses are needed for service operation. We hence also investigate the FCR impact on service quality and passenger demand lost.

We formulate the two problems as two optimization problems from a bus operator's perspective and find the bus fleet size, charging and discharging plans, and service frequency that can maximize the profit given the real energy market price and service quality sensitive passenger demand.

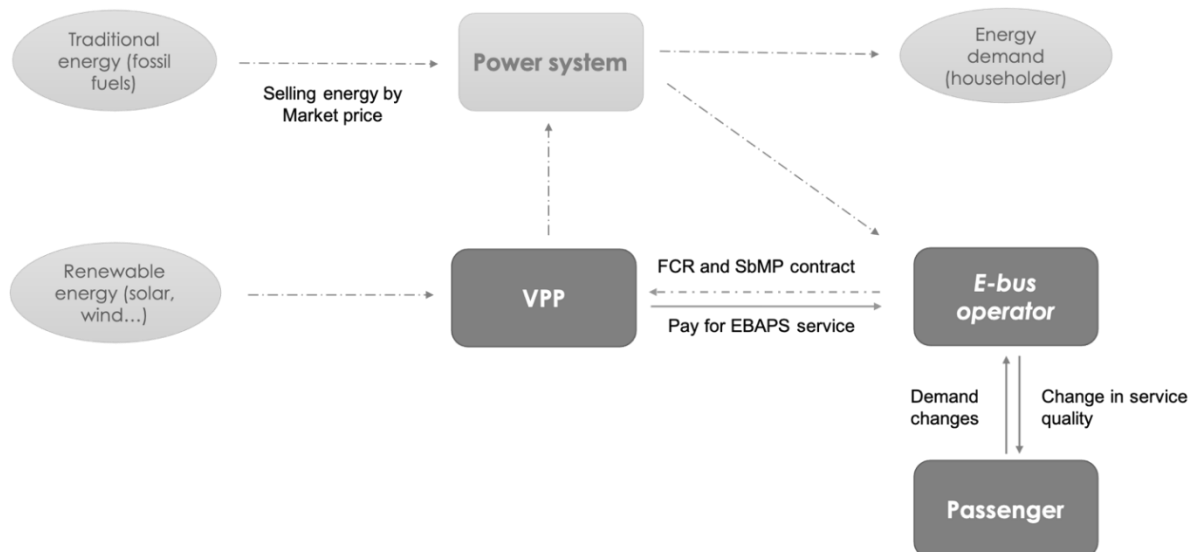


Figure 1. The VPP scheme with “EBaPS”. Dark grey shows the focus of this study.

The remainder of the paper is organized as follows. In Section 2, we deepen the literature review related to existing VPPs and regarding the key issues on the pathway of electrifying bus transit. In Section 3 we develop models for SbMP and FCR contracts respectively. The demand data collected from a real bus line in a Japanese city are introduced in Section 4, as well as energy market prices and specifications for battery capacity and energy exchange rates. The results of the case study are presented in Section 5 before the conclusions and further work is discussed in Section 6.

2 Literature review

2.1 Emerging energy exchange advancements

We base the proposed concept on the recent advancements in energy exchanges and smart grids. VPP-based applications have been evolving into practical products in the recent decade. There are a number of examples for companies to directly interact with the energy market. For example, to achieve the ultimate goal of zero emissions, Google buys electricity directly from a renewable project developer in the form of a power purchase agreement, then sells the power back into the grid and obtains Renewable Energy Credits, which can be applied to the energy used at Google data centers (Google, 2016). Another example is a Japanese company, Sunjunior, which installs and maintains solar generation systems for customers and recovers excess solar energy to provide renewable energy to the grid (Sunjunior, 2022). Like the solar energy generated by some customers, these small distributed energy resources (DERs) are hard to integrate into the grid. A project by Toshiba is aiming to achieve this by grouping batteries to flatten daily energy peaks (Toshiba, 2016). Further, as explained, VPPs can help to gather them to trade with the grid. A prominent example is the initiative of the government of South Australia which proposed the “SA VPP”. This is now the largest VPP with technologies supported by Tesla. In this VPP small amounts of energy stored in individual home batteries are aggregated to become large amounts of energy to help support the grid in times of need (The government of South Australia, 2018; Tesla, 2021).

DERs and their integration into VPPs have been a research focus for over a decade (Saboori et al. 2011; Pudjianto et al. 2007). With stable and efficient V2G technology, recent studies have noticed the potential of EVs as DERs contributing to VPPs. Alabi et al. (2021) develop a zero-carbon multi-energy system based on VPPs and EVs. The system assigns several flexible roles to EVs including vehicle-to-grid use, vehicle-to-electric use, vehicle-to-heat use, and vehicle-to-cooling use. The energy dispatching is conducted with VPPs as the system core. This system leverages the strength of VPPs to integrate multiple types of energy and illustrates the multi-flexibility potentials of EVs. Alhelou et al. (2020) introduce EVs into VPPs as the provider of frequency reserve to improve the stability and reliability of the smart power grid. Fan et al. (2020) also focus on integrating EVs into VPPs, and they develop a coordination algorithm for a VPP with photovoltaics inverters and EVs. Although not in a VPP environment, Li et al. (2018) propose an energy trading framework in distribution networks, noticing the potential contributions of DERs to the reliability

and security of the system operation and meanwhile the economic benefits of individual agents themselves. In light of these theoretical and practical supports, in this research, we let each electric bus be a DER and integrate a bus fleet into a VPP.

Kahlen et al. (2018) model a similar trade-off of transport provision versus providing energy services from the perspective of a car-sharing operator. Given an EV fleet for carsharing, the operator can charge and discharge the vehicles for electricity trading or rent them for rental income. They elaborately consider the dynamics of a real-time energy market, such as the bid price to charge and the asking price to discharge. Compared to car-sharing operators, the problems facing public transport operators appear to be more challenging. The service frequency or timetable deviations should not be too large, as otherwise, the operator loses the trust of passengers.

2.2 The electrification of bus transit

Several questions need to be answered to assist the decision-making of bus operators in the process of electrifying their services. First of all, bus operators may confront the long-term investment problem of fleet replacement. Pelletier et al. (2019) model this transition to an electric bus fleet as an integer programming problem, employing the number of buses and the number of chargers to be purchased as decision variables. Several types of buses and chargers with different specifications are assumed to be available. The model considers the discounted cost for this investment problem and updates the bus fleet every five years until 2050. Comello et al. (2021) narrow the focus on the break-even point of an electrification investment. They use a life-cycle model and “Levelized Cost of Electricity”, which is the revenue per electricity unit that can cover all expenses. In the existing literature, the revenue of this investment mostly comes from fareboxes, and the investment cost is compensated by national policies and subsidies (Hao et al. 2014; Wesseling, 2016) or from reduced operational costs due to lower energy costs and higher mileage per vehicle (Rogge et al. 2018).

Wu et al (2019) consider the electrification of a large bus fleet and its impact on the electricity grid. They formulate a Stackelberg game, the “Distribution Locational Marginal Price” algorithm where the bus operator reacts to the time-space optimized tariffs with adjusted service planning. Among others, they show the sensitivity of the grid loads with respect to battery capacities and prices. Other studies have looked in detail at the peak energy demand and resulting energy prices of bus fleets depending on the charging technology (Qin et al, 2019, Mohammed et al, 2017).

With respect to revenues gained depending on discharging times, we can only find studies that discuss strategies for private vehicles and shared taxi fleets. A shared autonomous electric vehicle simulation and optimization framework with FCR provision is given by Iacobucci et al. (2021), to explore the possibility of providing services to the grid for autonomous electric vehicles. Datta et al. (2019) propose a dynamic energy pricing regulated EV charging and discharging control strategy for three different EV operation modes,

namely, V2H (Vehicle to Home), G2V (Grid to Vehicle), and V2G. Mal et al. (2013) propose a system that effectively schedules charging and V2G operations for cost savings and peak load reduction to alleviate grid load during peak hours. In line with our study, they take advantage of off-peak charging benefits and generate revenue for the parking garage operator.

Further, the determination of the bus operation plans is increasingly complex by involving charging schedules. A large body of literature has been discussing this collection of problems. In general, these problems are solved by optimizations of some kind. The decision variables consider charging and dispatching schedules or consider both scheduling and infrastructure planning, e.g. the locations of charging stations, and the optimized objective also varies in a broad range. A methodology for the cost-optimized planning of charging schedules and charging infrastructure capacity for bus fleets is given by Rogge et al. (2018). They find the optimal charging and dispatching schedules for electric buses, the fleet composition, and the number of chargers with minimized operation and infrastructure costs for a given bus network. He et al. (2020) propose a model to optimize the charging scheduling and management for a fast-charging battery electric bus system minimizing total charging costs, which carries the potential for use in large-scale real-world bus networks. An (2020) jointly optimizes the locations of charging stations and the size of the electric bus fleet to minimize the total cost including construction, maintenance, and service operation costs. Liu et al. (2021) only consider charging costs and optimize the charging plans given limited chargers and time-varying electricity prices. Besides, several studies attempt to minimize the number of vehicles and chargers required, which also serve the idea of cost minimization. Liu and Ceder (2020) design a bi-objective integer programming to minimize both the number of vehicles and the number of chargers. Wen et al. (2016) minimize the number of vehicles and the total deadheading distance, while Wang et al. (2022) put emphasis on the number of chargers in their cost function. We note that most existing studies develop integer or mixed-integer programming as the decision variables are usually integer (e.g. number of buses required) or binary (charging or not). Our method employs service frequency per hour and allows continuous values, therefore we can rapidly find the global optimum and allow scalability to large fleet sizes solution but at the cost of not having a detailed plan for each bus.

Studies considering and modeling discharging for bus operation are few. Ke et al. (2020) optimize the battery charging and discharging at different periods by minimizing the total daily cost in an E-Bus system that allows battery swapping. The discharging and energy resales are conducted when the system residual electricity is higher than a threshold. Chen et al. (2017) propose an optimal coordinated charging and discharging strategy by deploying the energy storage system in the charging station to achieve maximum economic benefits. Recently, Rafique et al. (2022) consider an energy management problem from the viewpoint of a bus depot operator, allowing discharging to and trading with the real-time energy market, but the bus scheduling problem is not considered in their research. Manzolli et al. (2022) consider revenues from selling energy at market price and in particular focus on the battery degradation problem in bus-to-grid systems. They develop a mixed integer linear problem to describe the operational costs of a small fleet of minibuses that are used for charging as well as discharging. They show with a case study that the battery

replacement cost and aging is an important criterion to determine the profitability of a bus-to-grid scheme.

To conclude, we suggest this paper enriches the existing literature regarding the investment in bus transit electrification by the discussion of bus-to-grid scenarios. We introduce in the following a formulation that estimates the potential revenues from grid services under two types of contracts with the energy provider. As part of this, our paper extends the optimization methods for E-Bus scheduling problems by jointly considering charging, discharging, and dispatching. The following “fleet-based”, scalable model is efficient and we suggest useful for strategic planning.

3 Methodology

In order to find the bus operational tactics to achieve maximum profit, we model the aforementioned VPP scheme with a non-linear optimization. The decision variables in this research are the allocation of a given bus fleet characterized by a bus charging and discharging plan and the service frequency plan for a day. More specifically, for an SbMP contract, all decision variables are time-dependent. They are the service frequency $f(t)$, the number of buses connected to the grid $R(t)$, the system charging energy $E^+(t)$, and the system discharging energy $E^-(t)$. For an FCR contract, the former three decision variables remain while time-dependent discharging energy $E^-(t)$ is replaced by a static number of buses set aside at terminal K , which illustrates one of the major differences between these two types of contract. Fleet size is varied as an external input. The objective function is to maximize the profit for the bus operator. Given the distinctions between the aforementioned SbMP and FCR contracts, one model for each contract type is developed. For both models, charging points are assumed to be only at terminals and the number of charging points is always sufficient. As for the electric power of E-buses, we model an aggregate energy system of the total bus fleet at different periods, instead of considering the battery states of each bus. This is a simplification but allows us to develop a fast and robust solution approach.

3.1 Variables and parameters

The variables and parameters used in the models are shown in Table 1.

Table 1. Variables and parameters

Symbol	Description	Unit
Input parameters		
N	Bus fleet size	Bus
H	Bus line operation hours in one day	h
T	Travel time between terminals	h
S	The number of charging points at terminals	/
γ^-	Energy discharging rate per bus	kW

γ^+	Energy charging rate per bus	kW
η	Energy consumption per bus	kWh/km
$c_e(t)$	Energy market price in time t	\$/kWh
c_m	Maintenance cost for a bus per day	\$/day
ρ	The fee paid per passenger	\$
B	Battery capacity per bus	kWh
Z_{min}	Minimum state of system energy	%
Z_{max}	Maximum state of system energy	%
Z_0	The initial state of charge of system energy	%
$Y(t)$	Passenger demand in time t	pas
$P(f)$	Demand multiplier considering service frequency	%
κ_1, κ_2	Coefficients of demand multiplier	/
ε	The price of discharging power (FCR contract)	\$/kW
Decision Variables		
$f(t)$	Service frequency during time t	1/h
$R(t)$	Number of buses connected with the grid during t	Bus
$E^+(t)$	System charging energy during time t	kWh
$E^-(t)$	System discharging energy during t (SbMP contract)	kWh
K	Number of buses set aside at terminal (FCR contract)	Bus
Model output:		
Bus operation-related		
$U(t)$	The number of buses in operation at time t	Bus
System energy-related		
$E_c(t)$	System energy consumption during time t	kWh
$E(t)$	Aggregate energy of bus line at the end of t	kWh
E_0	Initial energy in the system	kWh
E_{max}	Battery capacity for the whole fleet	kWh
E_{min}	The minimum energy set to ensure running	kWh
Bus operator profits and costs		
P_g	Income from the grid per day	\$
P_p	Income from passengers per day	\$
$C_e(t)$	Cost of energy during time t	\$
C_m	Maintenance cost per day	\$

3.2 Basic formulations

We start the model description with some basic formulations that are common for both contracts. The bus service frequency $f(t)$ can change during different time-of-day periods. We approximate the number of

buses required to run in a period as in Eq. (1). This is a lower boundary as turnover times and delays can be further considered.

$$U(t) = 2Tf(t) \quad (1)$$

Formulations related to the energy of the aggregate system are shown in Eqs. (2) to (7). The available energy for the bus fleet at the beginning of a time interval is the energy available at the beginning of the previous period subtracting the consumed and discharged energy and adding the charged energy as in Eq. (2) for a single time step and in Eq. (3) for any time t where we assume that the bus fleet begins to operate with an initial energy E_0 as in Eq. (4). Assuming a constant energy consumption per bus, we can obtain the energy consumption of the whole fleet expressed in Eq. (5). To ensure a safety margin, each bus is assumed to have a minimum level of charge that the operator does not want to fall below. With this then also the minimum required level of energy for the whole fleet can be obtained with Eq. (6). Eq. (7) denotes the energy capacity of the fleet.

$$E(t) = E(t-1) - E_c(t) + E^+(t) - E^-(t) \quad (2)$$

$$E(t) = E_0 - \sum_{t'=1}^{t-1} E_c(t') + \sum_{t'=1}^{t-1} E^+(t') - \sum_{t'=1}^{t-1} E^-(t') \quad (3)$$

$$E_0 = BNZ_0 \quad (4)$$

$$E_c(t) = U(t)\eta \quad (5)$$

$$E_{min} = BNZ_{min} \quad (6)$$

$$E_{max} = BNZ_{max} \quad (7)$$

The objective function is profit maximization in one day which consists of the maintenance cost in Eq. (8), cost of energy charging in Eq. (9), revenue from the grid, and the profit obtained through passengers' fees as in Eq. (10). The grid revenue will be derived in the next sections as it depends on the type of contract. In Eq. (10) we presume that $Y(t)$ expresses the maximum amount of passenger demand that can be realized with a high enough service frequency. The lower the service frequency the fewer passengers will take the bus.

Demand sensitivity with respect to service frequency is difficult to estimate. It will vary depending on the availability of alternative modes, and will also vary in short and longer terms. We assume a logistic function as in Eq. (11) with two coefficients κ_1 and κ_2 . Their rationale and the values chosen will be discussed in the case study section based on some real data. We consider that an increase in service frequency will attract new passengers but with an upper bound to limit the total potential demand.

$$C_m = Nc_m \quad (8)$$

$$C_e(t) = E^+(t)c_e(t) \quad (9)$$

$$P_p(t) = \rho Y(t)P(f) \quad (10)$$

$$P(f) = \frac{2\kappa_2}{1 + e^{-\kappa_1 f}} - \kappa_2 \quad (11)$$

3.3 Formulations of SbMP contract

In the SbMP contract, bus operators can sell power to the grid by energy market price. This means that $E^-(t)$ becomes a decision variable with the profit from the grid services being determined by $E^-(t)$ as in Eq. (12).

$$P_g(t) = c_e(t)E^-(t) \quad (12)$$

With this, the nonlinear programming formulation can be derived where Eqs. (8) to (12) lead to the objective function shown with Eq. (13). Recall that the decision variables include the service frequency $f(t)$, the discharged energy $E^-(t)$, the charged energy $E^+(t)$, and the number of buses connected with the grid $R(t)$.

As for the constraints, firstly the number of running buses cannot be larger than the bus fleet size in Eq. (14). Buses that are not in operation can recharge energy or provide energy to the grid. $R(t)$, the number of buses connected with the grid in real-time, is subject to a set of constraints expressed in Eqs. (15) and (16). Eq. (15) is the fleet size constraint. Eq. (16) considers limited charging points.

From the perspective of the aggregate energy system, real-time energy for a bus fleet has the lower and upper limits shown in Eq. (17), where the lower bound is to ensure enough energy for turning back to the terminal as in Eq. (18). In particular, the amount of charging and discharging will be limited by the energy exchange rate, the number of buses stopping in the terminal in Eq. (19), and the battery capacity in Eq. (20). At last, the decision variables should take non-negative values according to Eq. (21).

Problem SbMP

$$\max_{f(t), E^-(t), E^+(t), R(t), \forall t \in \{1, 2, \dots, H\}} P = \sum_t (P_p(t) + P_g(t) - C_e(t)) - C_m \quad (13)$$

Subject to:

$$U(t) \leq N, \forall t \in \{1, 2, \dots, H\} \quad (14)$$

$$R(t) \leq N - U(t), \forall t \in \{1, 2, \dots, H\} \quad (15)$$

$$R(t) \leq S, \forall t \in \{1, 2, \dots, H\} \quad (16)$$

$$E_{min} \leq E(t) \leq E_{max}, \forall t \in \{1, 2, \dots, H\} \quad (17)$$

$$E_c(t)Tf(t) \leq E_{min}, \forall t \in \{1, 2, \dots, H\} \quad (18)$$

$$\frac{E^-(t)}{\gamma^-} + \frac{E^+(t)}{\gamma^+} \leq R(t), \forall t \in \{1, 2, \dots, H\} \quad (19)$$

$$E^+(t) - E^-(t) \leq R(t)B, \forall t \in \{1, 2, \dots, H\} \quad (20)$$

$$f(t), E^-(t), E^+(t), R(t) \geq 0, \forall t \in \{1, 2, \dots, H\} \quad (21)$$

3.4 Formulations of FCR contract

In this contract, the bus operator needs to set aside a number of buses at the charging point to fulfill the FCR contract. The profit from energy services is hence assumed to be determined by the number of buses connected to the grid K as in Eq. (22).

$$P_g = \varepsilon K \gamma^- \quad (22)$$

Therefore, the decision variables and some constraints differ from those in the SbMP contract. For the decision variables of the objective function in Eq. (25) the discharging energy $E^-(t)$ is replaced by the number of buses K . The formulations of energy will also change to Eqs. (23) and (24).

$$E(t) = E(t-1) - E_c(t) + E^+(t) \quad (23)$$

$$E(t) = E_0 - \sum_{t'=1}^{t-1} E_c(t') + \sum_{t'=1}^{t-1} E^+(t') \quad (24)$$

The constraints regarding the bus fleet and aggregate energy are the same as those in the previous section expressed in Eqs. (14) to (18). Only the constraints regarding charging and discharging energy and the new decision variable K vary. K should always be smaller than the real-time number of buses being able to connect to the grid in every time period as in Eq. (26). Further, the amount of charging energy is limited by the energy charging rate and battery capacity as in Eqs. (27) and (28). Since the buses connected to the grid are not necessarily discharging to the grid all the time, these buses can also be charged. We omit the system

discharging energy in Eq. (24) considering that the amount of discharged energy, which is only for emergencies, is low in this contract.

Problem FCR

$$\max_{K, f(t), E^+(t), R(t), \forall t \in \{1, 2, \dots, H\}} P = P_g - C_m + \sum_t (P_p(t) - C_e(t)) \quad (25)$$

Subject to Eq. (14) to (18) as well as:

$$K \leq R(t), \forall t \in \{1, 2, \dots, H\} \quad (26)$$

$$E^+(t) \leq \gamma^+ R(t), \forall t \in \{1, 2, \dots, H\} \quad (27)$$

$$E^+(t) \leq R(t)B, \forall t \in \{1, 2, \dots, H\} \quad (28)$$

$$K, f(t), E^+(t), R(t) \geq 0, \forall t \in \{1, 2, \dots, H\} \quad (29)$$

3.5 Problem solving

All the constraints introduced in the previous two sections are linear functions and the feasible set is convex. The objective function uses C_m , $C_e(t)$, and P_g which are also all obtained from linear functions and $P_p(t)$ is derived from the convex section of a logistic function. This means that the objective function is convex. Therefore, this is a non-linear convex optimization problem so that the exact solution of the global optimum can be easily found. We choose the “interior-point” algorithm incorporated by MATLAB R2021a to solve this problem.

4 Case study and input data

4.1 Bus demand and frequency

We take the smart card data of a bus line from a mid-size Japanese city as an example. The demand for the bus follows a typical morning and evening peak pattern as shown in Fig. 2. From the bus GPS data, the bus fleet size and travel time between terminals of this bus line can be obtained.

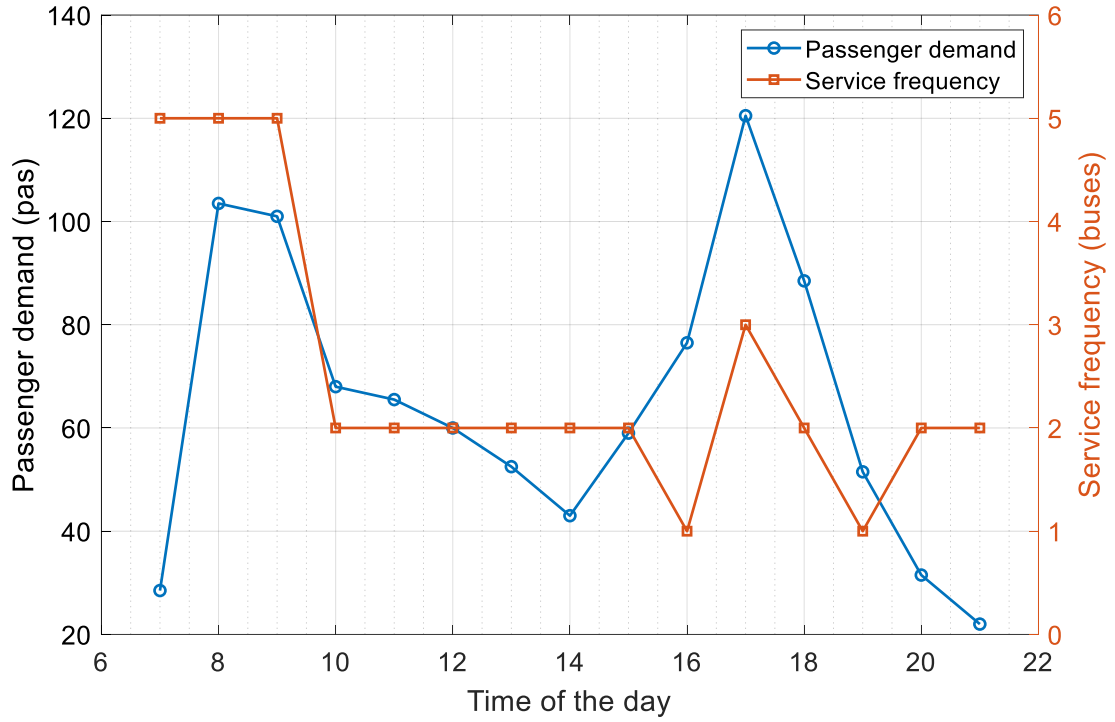


Figure 2. Observed passenger demand and service frequency by time of the day of the example line

The service frequency of the line is between two and five buses per hour for most of the operating hours according to the actual bus timetable. Since the service is already in operation, some kind of demand equilibrium has likely been reached. In other words, even if the service frequency is increased, the demand is unlikely to significantly increase. Therefore, we assume that when $f = 3$, the value of passenger demand multiplier $P(f)$ should be fairly close to 1, and the passenger demand is sensitive to frequency reductions but not, or less, to service frequency increases. This means that the demand multiplier keeps approaching but cannot exceed significantly one even if the service frequency is improved to a much higher value. We note that this is a conservative assumption for our model as the potential to increase demand with more frequency would also mean more buses and more potential to provide grid services in off-peak hours. We further make a conservative “worst case” assumption, compared to the present reference case, in terms of potential demand loss if the service frequency is reduced. We assume that this demand loss is high so that providing grid services with the current fleet will lead to income losses from passenger revenue. Based on these arguments we choose the values of the coefficients κ_1 and κ_2 for the formulation of $P(f)$ as shown in Table 2, where κ_2 determines the maximum demand.

4.2 Energy market price

Energy market prices vary significantly by time of day, sometimes even minute by minute. We obtain the real-time Japan energy market price for every half-hour interval of a typical day from the Japan Electric Power eXchange website (JEPX, 2022). Market prices further differ significantly by season. Following Japanese common definitions and schedule changes at the beginning of April and October, we regard April to September as summer and October to March as winter. The average energy prices during the bus operation

time in the summer and winter of 2016, the year for which the bus smart card data are available to us, are given in Fig. 3. The average price of energy is higher in winter than in summer and the prices have different time-of-day patterns. In winter, there are two peaks, in the morning and evening, whereas there is only an evening peak in the summer. To note is that the energy peaks occur at similar times as the commuting peaks (Fig. 2). If the travel demand peaks could be spread or be separated from the energy peaks we expect the proposed concept of buses as part of a VPP to become even more beneficial. We note that only bus operating hours are considered for two reasons. Firstly, the energy price at non-operating hours, which are usually during the late night and early morning, is low and stable. It is therefore reasonable to assume that the operator charges the vehicles to full during non-operating hours. Secondly, the operator can only make a profit from discharging in hours when the price is higher than the charging cost, so it would not be an optimization problem.

Another key input for the FCR contract is ε . It is the price of discharging power per bus, paying for a bus's capability of providing energy to the power grid on urgent requests at any time. Therefore, it has to be higher than the energy market price, otherwise, the operators might prefer to trade the energy at the market price. Here we use 0.2 \$/kW for this power price which is twice the peak energy price.

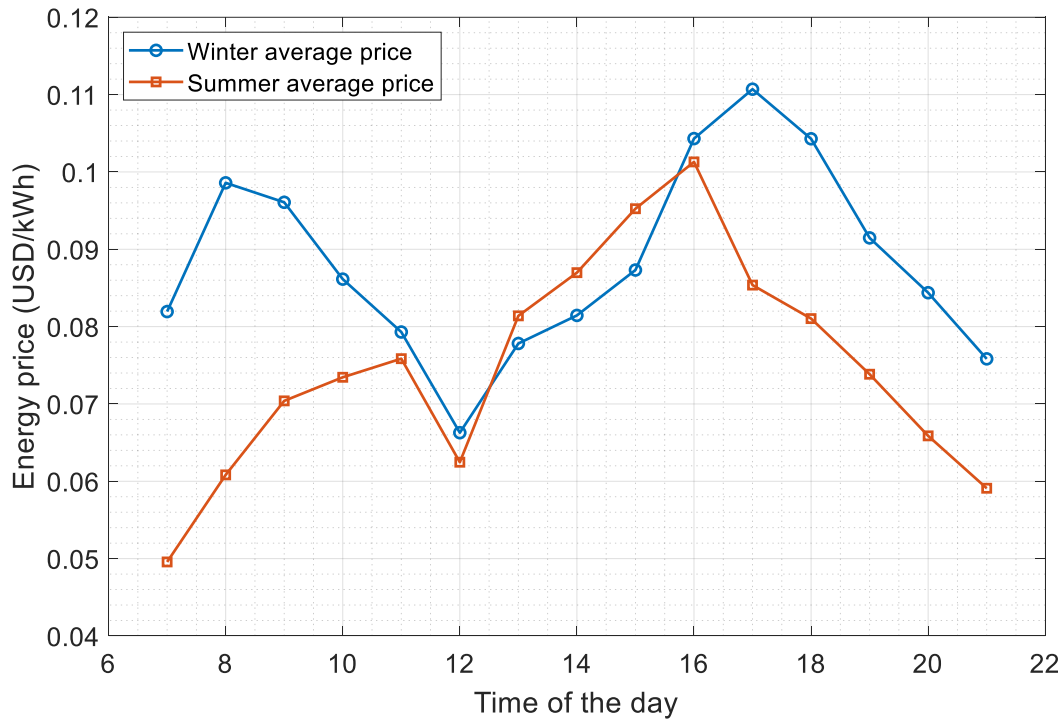


Figure 3. Average energy market price in summer and winter

4.3 Bus operational costs, battery performance, and energy exchange rates

The energy consumption and battery performance of city transit electric buses operating were evaluated by Gao et al. (2017). They show that the battery capacity and charger power vary by brand and size. Battery capacity ranges from 53 kWh to 548 kWh as they are, among others, also related to the different charging methods. We assume the average to be 200 kWh and the range to be tested from 50 kWh to 500 kWh. To

note is also that we only consider charging at terminals. A reasonable value for the average battery energy consumption of an electric bus appears to be 1.35 kWh/km but the value will depend on geography and climatic conditions (e.g. need for air conditioning). The charging rate can vary from 0.2 C to 10 C, and the discharging rate can vary from 0.2 C to 1 C (the capacity of a battery is commonly rated at 1 C). Taken together, we set the average charging rate as 60 kW and a smaller value as 40 for discharging rate. For sensitivity analysis purposes, we vary the charging rate from 0 to 200 kW and discharging rate from 0 to 100 kW.

It is reported that the average maintenance cost for an electric bus is 0.34 USD per kilometer (American Public Power Association, 2019). A maintenance cost of 6 USD per day is then assumed for this 17km bus line in our case study, regardless of how many trips a bus can make in a day.

Finally, an initial state of charge to start the day and a minimum state of charge to leave the terminal have to be specified for the buses. As explained before we assume that it is reasonable that all E-buses are charged at night when the energy prices are low so that they start the day with a full battery load. Also, we assume that the operator wants to avoid any en-route operational problems due to the shortage of electricity so 30% of the battery capacity is used for the minimum state.

To sum up, all the input values for the base case are shown in Table 2.

Table 2. The summary of the input parameters

Bus operation-related input		Energy-related input	
Variables	Value	Variables	Value
ρ	2 USD/pas	$c_e(t)$	Illustrated in Fig. 3
$Y(t)$	Illustrated in Fig. 2	B	200 kWh
H	15 h	γ^-	40 kW
N	5 to 18 Buses	γ^+	60 kW
T	1.15 h	η	1.35 kWh/km
$P(f)$	$\kappa_1 = -1.2, \kappa_2 = 1$	ε	0.2 USD/kW
S	20 Charging Points	Z_{min}	30%
c_m	6 USD/bus per day	Z_{max}	100%
		Z_0	100%

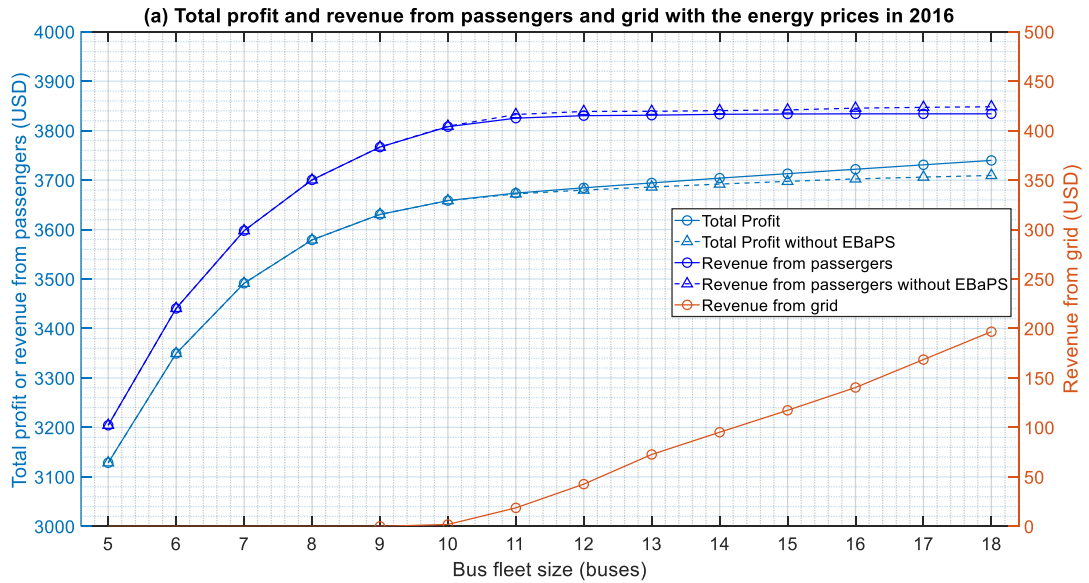
5 Results

5.1 SbMP contract

Effect of fleet size

Fig. 4(a) shows the expected maximum profits and revenue splits with the input parameters for different sizes of bus fleets after solving Problem SbMP. We vary the fleet size from 5 to 18 buses. The low fleet sizes provide no room for EBaPS to generate revenues from energy sales. In general, we observe that – as one would expect and hope for - with our parameter settings the revenue from grid services is significantly smaller than passenger revenue, meaning that the primary role of bus fleets remains providing transportation services and grid services only take a secondary role. Nevertheless, we suggest that the additional profit that could be obtained from grid services is non-neglectable. The bus operator will welcome a small increase in total profit with the introduction of EBaPS and SbMP contracts, which can be achieved if the size of the bus fleet is larger than 10. Currently, the studied line operates with 18 buses. At this fleet size, our model suggests that the total profit could increase from 3709 USD to 3739 USD with EBaPS. Considering potential costs for the investment in buses, which are not considered in our model, we suggest a reasonable fleet size might, however, be 14 (15) buses. This fleet can earn 3704 (3713) USD for the operator and maintain the profit level with four (three) buses fewer. Besides, we can see that the decrease in the revenue from passengers due to the fleets' providing grid services is insignificant. In real operations, the passengers leaving the bus transit system can use alternative modes and the slight frequency drop might not harm the perceived reliability of the system.

Finally, with Fig. 4(b) we illustrate the case of increased energy tariffs. A doubling of prices compared to 2016 energy tariffs is close to the situation in 2022. The figure illustrates that revenues from the grid are more than doubled, which is partly due to some minor service adjustments. The overall profit increases slightly from 3739 USD to 3774 USD and the margin to the case without EBaPS is more than doubled from 30 USD to 82 USD, considering that buses also require more resources to purchase energy.



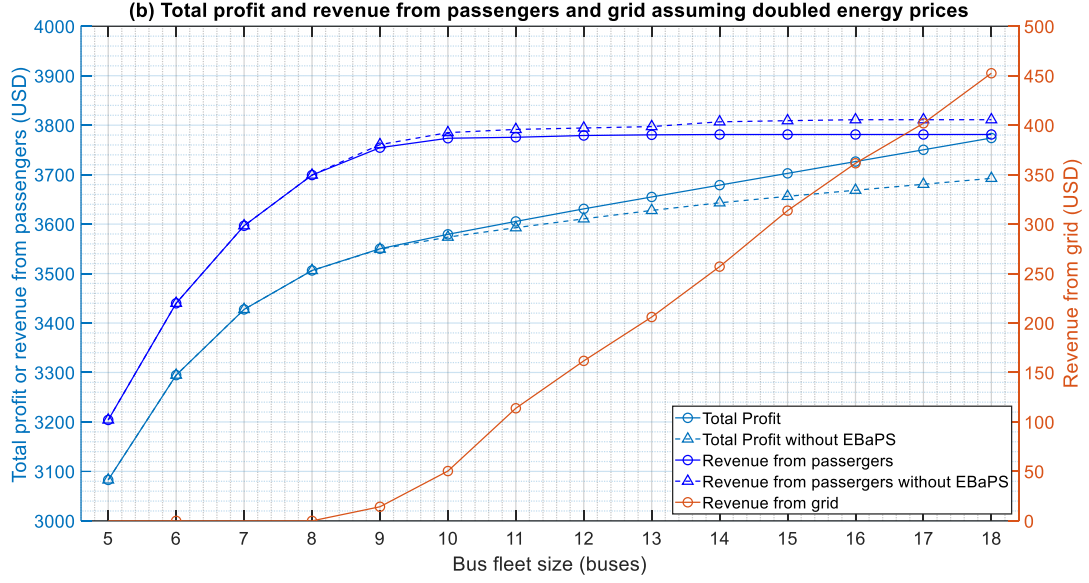


Figure 4. The profitability of the SbMP contract with EBaPS given different fleet sizes: a) with the energy prices in 2016 as in Fig. 3 and b) assuming doubled energy prices

Timetable in summer and winter

We now illustrate the effects of different seasonal energy prices. A bus service cannot change the schedule too often. However, since the energy prices in summer and winter differ significantly, some seasonal service adjustments might be reasonable in response. We illustrate the summer and winter service frequencies and energy exchange patterns in Fig. 5.

The passenger demand is presumed to be identical in summer and winter. Comparing Figs. 5(a) and (c), we can observe some changes in the service frequency. Since the adjustments are fairly small, it indicates that the extra effort of seasonal service adjustment to meet the fluctuation of energy prices is manageable, which further confirms the feasibility of the proposed concept.

From Figs. 5(b) and (d) we learn that instead the changes in the charging and discharging hours are more significant. In summer, the electricity price has only one afternoon peak slightly before the evening commuting peak hours, whereas in the winter there are a morning and an evening peak (partly due to less availability of solar energy). The summer energy price peaks overlap with the busiest demand period. Therefore, to maintain the service frequency and satisfy the passenger demand peak, the amount of discharge is limited and the timing of discharging does not precisely coincide with the price peak. As for charging, a peak is observed at noon to have sufficient electricity to serve the remainder of the day and avoid the high afternoon energy prices. Also, in winter there is a charging peak at lunchtime but it is longer and starts earlier. This allows the bus operator to sell some energy in the early morning hours when the energy price is also high. Moreover, we find that the revenue gained from the grid is higher in winter. This occurs because of the two energy peaks in winter that offer more trade-off opportunities.

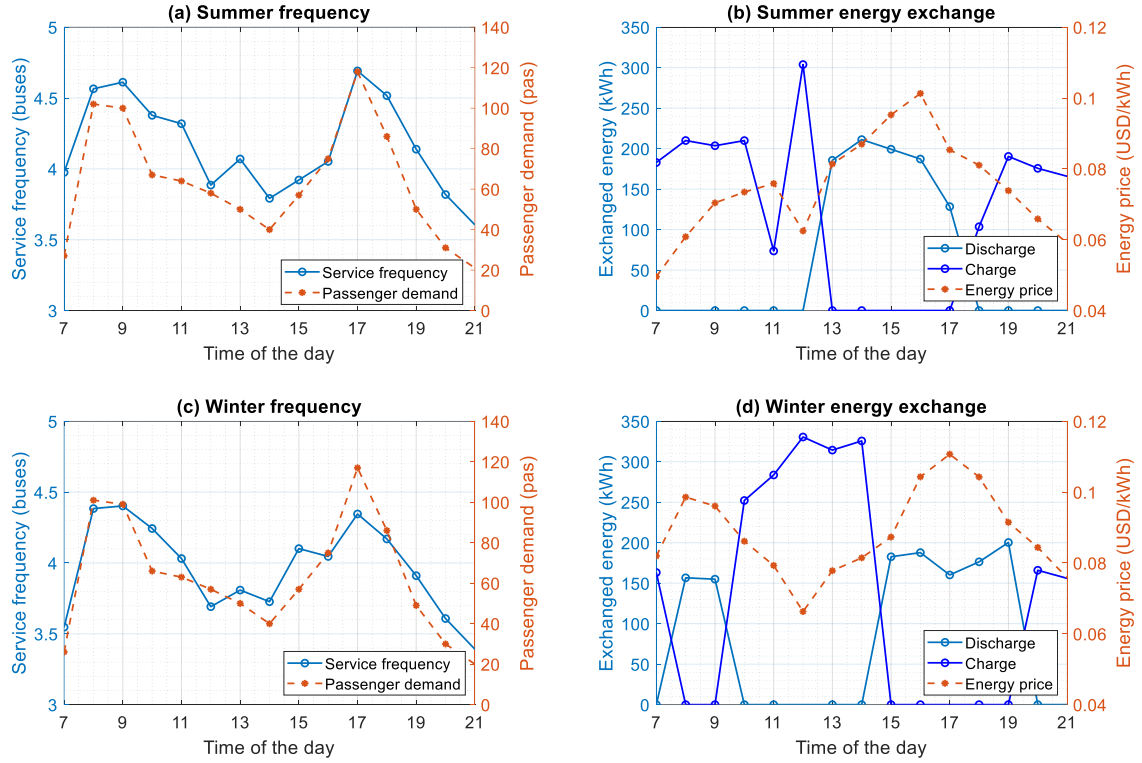


Figure 5. The service frequency and energy conditions in the summer and winter under the SbMP contract

Sensitivity analysis

We conduct a range of sensitivity analyses concerning the key input parameters. The range of the input parameters has been discussed in Section 4. More specifically, we test the effect of discharging rate γ^- , energy consumption rate η , and battery capacity B on the optimal decision variables and the bus operators' profitability. The results related to the discharging rate are provided in Fig. 6 as an example. The number of buses in the fleet is fixed at 14. Fig. 6(a) shows the revenues and profits and Fig. 6(b) shows the optimal frequency and energy exchange in every period, varying the discharging rate from 0 to 100 kW.

It can be found in Fig. 6(a) that, as expected, the faster the charging rate, the higher the profit. The increased profits arise from grid revenue, and the revenue from passengers is almost the same. Only when the discharge rate is as low as 0 to 20 kW/bus, which means that the buses barely participate in grid service, does the revenue from passengers become slightly higher. More insights can be gained with Fig. 6(b). As shown in the graph of the optimal service frequency, most of the trends are similar, but, during the evening energy price peak periods, with the increase of the discharge rate, the service frequency is slightly reduced. When the discharging rate is high, the fleet can take advantage of the periods of higher prices to receive revenue from the grid in a shorter time. The charging amount increases at noon when the prices are low for more energy to discharge in the evening. However, due to the large passenger demand in the evening, the fleet still needs to ensure service quality, and the reduction of the service frequency cannot be too large. To conclude, buses with higher discharge rates are beneficial for providing grid services, but from the perspective of the

operator, the purchase cost of buses with high discharging rates and their battery life and discharging cost should be considered. Additional figures related to the other two parameters are omitted for brevity. The results are as expected and illustrate how lower energy consumption and larger battery capacity, under suitable charging rates, from 40 to 120 kW, are profitable to the bus operators.



Figure 6. Sensitivity analysis for the discharging rate, the effect of varying discharging rates on (a) the operator's revenues and profits, (b) the optimal decision variables

5.2 FCR contract

We now turn to the second type of contract where the buses fulfill the function of a backup system for energy supply. We remind, that hence the revenue is determined by the number of buses being connected to the grid and ready to discharge if needed.

Effect of fleet size

The current 18-bus fleet can earn a total profit of 3709 USD for an operational day without participating in the grid services. The profit reaches up to 3771 USD with a fleet of the same size if the operator signed the

FCR contract. Instead, if the bus operator plans to electrify the bus fleet and keep the same level of profit per operational day as before, only 13 buses can earn a profit of 3711 USD. In the doubled price situation shown in Fig. 7(b), by signing the FCR contract, 18 buses can earn a profit of 3837 USD, while only 3693 USD can be earned without B2G (lower than in Fig. 7(a) as the charging cost is increased). Note here that the price of discharging power ε is also doubled in Fig. 7(b). Fig. 7 also shows that after participating in grid services with the FCR contract, with the same bus fleet size, the bus operator can obtain a higher total profit. Compared to the SbMP case in Fig. 4, we observe that both the revenue from grid services and the revenue from passengers are lower, but at the same time, the gap between the total profits with and without EBaPS is enlarged. In other words, EBaPS earn more additional total profit for the bus company in this FCR case. This mainly is the outcome of the slightly reduced number of buses used for transportation service and the accordingly reduced operation cost.

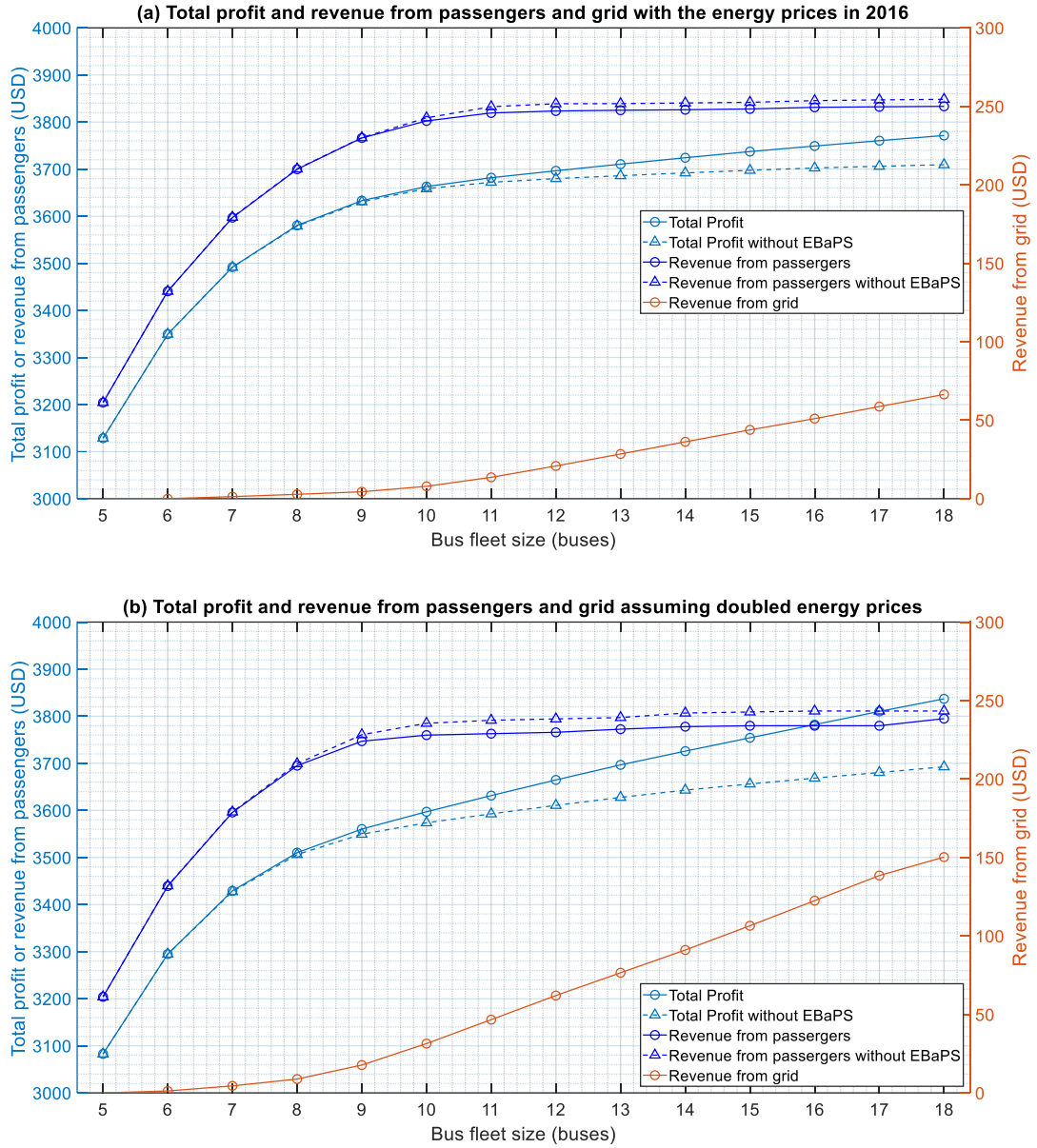


Figure 7. The profitability of the FCR contract with EBaPS given different fleet sizes a) with the energy prices in 2016 as in Fig. 3 and b) assuming doubled energy prices

Timetable in summer and winter

Since in the FCR contract the discharging is independent of the variations in the energy prices, the service frequency is less impacted. Fig. 8 illustrates that due to the different time-of-day energy prices in summer and winter, the charging time varies, which will also, to some degree, change the service frequency. In general, the service frequencies in both seasons are stable over the day, as there is no need to trade off with the energy prices. The time points at which both passenger demand and electricity price are low are usually selected as the charging timings. Overall, the FCR contract eases the difficulty of balancing transportation and grid services and can earn more profits for the bus company. For brevity, we omit the sensitivity analysis with respect to the input parameter variations analyzed for the SbMP contract, as we do not find markable

differences leading to further conclusions.

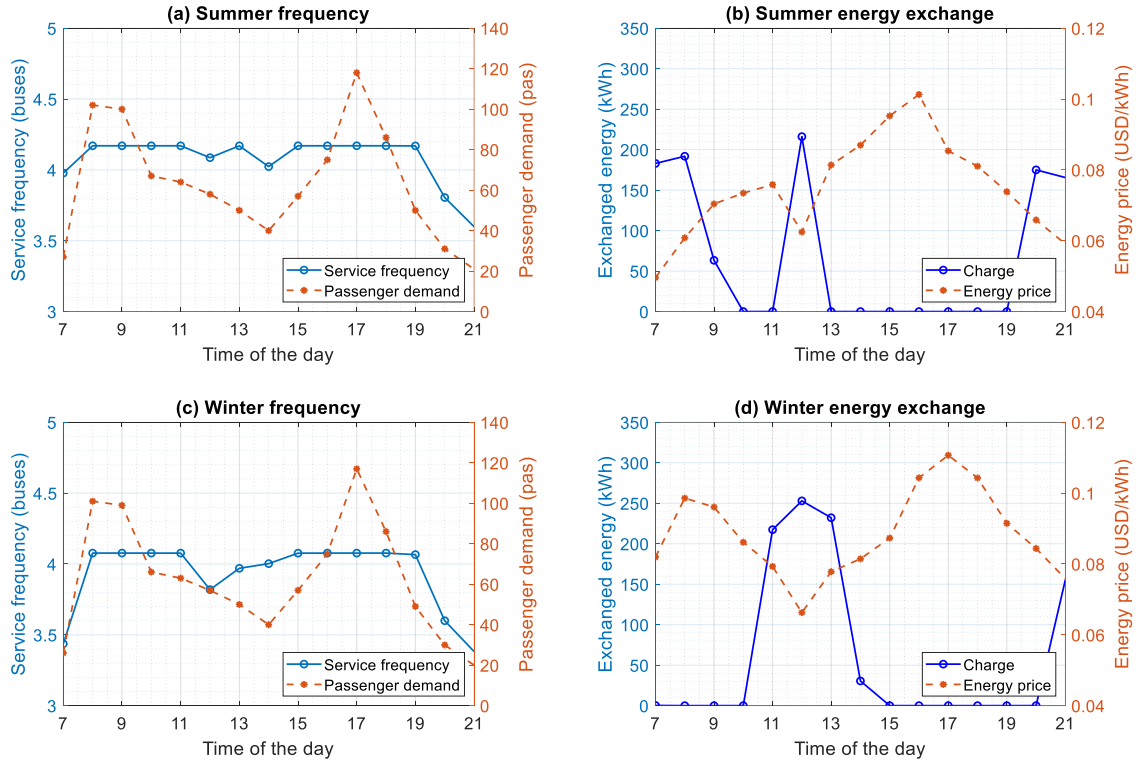


Figure 8. The service frequency and energy conditions in summer and winter under the FCR contract

6 Conclusion

6.1 Findings

The advancement of vehicle electrification and two-way interactions between these vehicles and energy grids creates also additional opportunities for public transport operators. To explore this, in this study, a Virtual Power Plant (VPP) system in which E-buses act as a storage battery that can discharge at any time of the day is discussed. This is expected to motivate the electrification of the bus fleet as it helps the bus operator to open up a new source of revenue. The main novelty of this paper is twofold: Firstly, we model the problem at an aggregate level which allows one to model large fleet sizes. Secondly, based on this VPP, two types of contracts, SbMP (Sale by market price) and FCR (Frequency Reserve Control) are modeled. To illustrate the feasibility of the concept, we optimize the bus fleet allocation and energy exchange plans that can maximize the operator's profit. The main findings are summarized as follows.

- 1) A higher total profit can be obtained by participating in grid services in all case studies. The additional profits are, however, as expected, lower than revenues from the farebox. We find this under “conservative assumptions”, i.e. those that do not favor the V2G concept.
- 2) As for the bus fleet size, it is found that the bus operator can achieve the same level of revenue with

a smaller bus fleet than that before the electrification. At the same time, if there is latent demand that can be attracted if the service frequency is higher, we suggest that the V2G concept can be an incentive for the bus operator to increase the fleet size.

- 3) Under the SbMP contract, the optimal bus timetable changes slightly with the market energy price in different seasons. The main determinant of the service frequency remains, however, to be the passenger demand.
- 4) In the sensitivity analysis, a larger discharging rate, less energy consumption, higher passenger fare, higher discharging price, and larger battery capacity are expected to lead to more profit for the bus operators. This discussion is important considering that charging technology and battery capacities and efficiencies are expected to further improve in the future.
- 5) Comparing the SbMP and FCR contracts, the SbMP contract brings more additional revenue from the grid to the bus operator. In practical applications, considering wider benefits and investment costs, the FCR contract may require compensation or subsidies. We remind that the additional environmental benefits of our proposed scheme are not included in this operator revenue.

6.2 Further work

Our study modeled the EBaPS problem from an aggregate perspective considering service frequency and not detailed charging and discharging schedules of each bus. We, therefore, refer to it as a “strategic model” but we acknowledge that implementation will clearly require the detailed consideration of charging and discharging schedules for each bus. Therefore, the straightforward further work is to develop “microscopic models” similar to Manzolli et al. (2022) to elaborate on the schedules and real-time battery status of each bus. This comes at the cost of losing the scalability to large-scale city-wide scenarios. We suggest the here proposed “mesoscopic approach” is useful for generally understanding the feasibility of the proposed concept and for modeling the average performance of large bus fleets. We analyzed a single bus line but the results are scaleable to a larger network if the lines are all operated independently of each other. If buses are, however, shared between different lines, modifications are needed to calculate the required fleet size. Further, the situations in which the E-bus services compete for revenues with other bus operators would lead to different demand sensitivity functions that could be explored.

A second related research direction is to consider battery specifications and technical issues of charging and discharging require in more detail. More specifically, the discharging cost in the current technical stage might not be negligible and battery discharging might accelerate battery aging. The impact of battery aging should not be ignored in the long-term adoption of electric battery bus fleets considering year-to-year battery degradation. We also noted in our discussion on the parameter settings that some of these are dependent on season, climate, and geography. A third, interdisciplinary topic is to model the problem with the integration of the grid systems, that is, considering the light grey boxes in Fig. 1 in more detail. To illustrate the impacts of “Bus-to-Grid” on the grid systems, a realistic grid network topology and grid-side settings are necessary. The energy brought back to the grid and its impacts on the energy market might be needed by the grid provider to evaluate the feasibility to sign contracts with the bus operators. It will also be practical and helpful for

stabilizing the energy market if short-term predictions on energy prices and their fluctuation are integrated into the model. Considering such aspects and, for example, saved emissions could also lead to studies where not the bus operator's profit but the general social welfare is maximized.

CRedit authorship contribution statement

Fan Fei: Conceptualization, Methodology, Formal analysis, Writing - original draft, Visualization. Wenzhe Sun: Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing, Visualization. Riccardo Iacobucci: Conceptualization, Methodology. Jan-Dirk Schmöcker: Conceptualization, Methodology, Supervision, Writing - review & editing.

Declaration of competing interest

The authors declared that there is no conflict of interest.

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