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Title: Energy Consumption and Battery Sizing for Different Types of Electric Bus Service.

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Abstract

With the deployment of battery electric buses (BEB) increasing worldwide, proper battery sizing becomes more critical for operators as it dictates bus driving range and costs. In this paper, we present a battery sizing framework based on comprehensive energy needs assessment for BEB. The bus operating conditions are first defined for different types of bus service (City, intercity, shuttle, regional, rapid-transit). Then, BEB energy consumption is evaluated using a comprehensive energy model developed by the authors. Finally, the required battery size is estimated for different types of charging infrastructure. Modeling results show that BEB energy consumption is sensitive to bus service type, ranging widely between 2-4.6 kWh/km, and that intercity buses require the largest battery size (320-680 kWh). A practical finding for operators from our Paris case study is that city bus batteries are unnecessarily oversized to accommodate a typically small fraction of trips in rare extreme cold weather conditions.

1. Introduction

Battery electric buses (BEB) present the most promising alternative to replace diesel bus (DB) fleets and reduce their environmental burden [1]–[3], however, their massive deployment is subject to many challenges, namely the bus limited driving range and high capital costs [4], [5]. Unlike DB, BEB endure a reduced driving range due to the limited energy stored in the battery onboard [5], [6]. In addition, BEB suffer poor economic performance when compared to DB or any other alternative bus technology, and this is mainly driven by the high cost of the battery pack [7], [8]. The battery energy capacity is mainly oversized to increase the BEB driving range and avoid any disruption in operation, however, this increases the capital and operating costs of the already-expensive technology [9], making BEB an unattractive solution for bus operators.

This is why proper battery sizing is a key factor for operators, which is the objective and main contribution of this paper. Since the battery is the only energy and power source onboard with no other backup systems, it should be sized appropriately to supply all BEB energy needs. These energy needs include the propulsion system energy consumption, the heating ventilating and air conditioning (HVAC) unit, and other auxiliaries essential for the BEB operation, such as the pneumatic braking system and the battery thermal management system (BTMS).

However, proper battery sizing is a challenging endeavor since BEB energy needs vary as function of the different bus real-world operating conditions [10]–[13], namely the driving and weather conditions, and passenger occupancy levels. Driving conditions are characterized by the bus velocity profile, driving behavior, trip distance and duration, road topography, and the number of stops along the route. These primarily affect the energy behavior of the propulsion system in the BEB [6], [14], [15]. Moreover, the level of passenger occupancy influences the energy consumption of the bus due to the additional weight onboard and the varying thermal comfort conditions depending on the number of passengers occupying the bus [6], [16]. On the

other hand, weather conditions, such as temperature and solar flux intensity, impact the bus thermal needs and thus affect the HVAC unit energy consumption [17]–[20].

The bus operating conditions are determined by the type of bus service. The main types of public bus service are city buses, bus rapid transit (BRT), shuttle buses, regional buses, and intercity buses. City buses and BRT mainly operate within and near city centers all day long, with the only difference being that BRT run on specific corridors along the route to avoid traffic congestion. Shuttle buses generally travel regularly from one or more locations to a single destination, such as airport shuttle buses or university shuttles. Regional bus service connects cities with their neighboring suburbs or small towns, whereas intercity buses travel between cities and mainly for long distances. The driving conditions and levels of passengers' occupancy highly vary among the different types of bus service.

In addition, the choice of charging infrastructure affects the required bus battery size [21], [22]. Charging the BEB during the night outside the bus service hours requires a large battery as it should be capable of supplying the entire BEB energy needs throughout the day. For such a charging method, slow chargers are typically installed at the bus depot since this is the least costly solution when enough time is available to charge the buses [23]. On the other hand, implementing on-route charging with costlier fast chargers allows multiple charging events of relatively short duration each throughout the bus service time, which creates an opportunity for reducing the battery size [24]. Multiple charging stations are required in this case including charging at the BEB terminal station and/or any stop station along the BEB route [25], [26]. The different types of bus service impose different constraints on the choice of the charging method.

Consequently, a battery sizing framework based on the precise assessment of the BEB real-world energy needs and adopted charging infrastructure is necessary and is the key contribution of this paper as this has not been previously addressed in the literature.

Most of the studies in the literature focus on assessing the energy needs and battery sizing requirements for public transport city buses. Gao et al. [27] evaluate the required battery sizing and recharging needs for a city bus transit service focusing on the impact of ultra-fast opportunity charging on the required battery size and bus service reliability. Rogge et al. [28] study the potential of implementing a fast-charging infrastructure for different city bus lines based on real-world data and its impact on battery sizing and charging power. Teichert et al. [29] optimize the battery size and charging infrastructure to minimize the total costs of ownership of electric city buses. Kunith et al. [30] propose a framework to optimize battery sizing and location of fast chargers along the bus route to minimize the total cost of ownership of electric city buses. Liu and Song [31] investigate the potential of dynamic wireless charging to reduce the required battery size for city buses considering uncertainties in the bus energy needs. Sinhuber et al. [32] evaluate the energy needs and required battery sizing for different city bus routes. [33] introduces a battery sizing approach for plug-in hybrid electric buses, focusing on the impact of trip distance on the bus battery size and energy management strategy for urban buses.

The majority of the presented studies evaluates the BEB energy needs using relatively simple energy models where the propulsion system components, such as the electric machine, battery, and transmission systems, are considered to have a constant efficiency at all operating conditions as presented in [27], [28], [31], [32], while very few studies discuss in detail the impact of the different bus driving cycle and passengers load on its energy needs as presented in [34] and [35]. Some studies do analyze the energy demand uncertainty in electric buses and the impact on the bus charging needs [36]. Such approaches give a useful first estimation but does not accurately reflect the real-world energy needs of the BEB as the propulsion system efficiency is highly affected by the driving conditions. In addition, these studies consider a fixed HVAC load during the BEB operation ignoring the dynamic heat transfer phenomena that highly impact the HVAC unit energy consumption. All the presented studies either ignore the auxiliary's energy consumption or consider it as a constant input to the energy model which sacrifices the model accuracy. Besides, the bus real-world operating conditions are misestimated by using standardized drive cycles and fixed passengers' occupancy.

Very few studies assess the battery sizing for different types of public bus service other than city buses. El-Taweel and Farag [37] evaluates the energy needs and charging requirements for an intercity bus. The study focuses on scheduling the BEB charging due to the infrastructure constraints imposed by the route characteristics considering a fixed battery size. [38] evaluates the energy needs and well-to-wheel greenhouse gas emissions for city buses operating in the BRT system in Brazil for a variety of bus powertrains. [39] studies the charging infrastructure needs of intercity coach buses to minimize their waiting time at the charging stations. Korsesthakarn and Sripakagorn [40] study the energy needs of a university campus electric shuttle bus focusing on charging scheduling to reduce the BEB queue time at the charging stations. No study evaluates the energy needs and battery size requirement for other types of public bus service.

Based on what has been presented, the following main gaps are underlined in the recent literature:

- Very few studies propose a precise and comprehensive assessment of total BEB energy needs considering all energy systems including propulsion, HVAC, and auxiliaries.
- Most studies rely on standardized driving cycles and assume stable weather conditions and fixed passengers' occupancy, which differs significantly from real-world operating conditions. This leads to a misestimation of the total BEB energy needs and required battery size.
- To the authors' best knowledge, no study in the literature evaluates the different energy needs and battery sizing requirements for different types of bus services, and no study has yet proposed a battery sizing framework in this context.

Therefore, based on the above-identified gaps in the literature, this study proposes a battery sizing framework based on a precise and comprehensive assessment of the BEB real-world energy needs for different types of public bus service. This paper is novel in three ways:

1. It provides a precise assessment of the comprehensive BEB energy needs considering its propulsion, HVAC, and auxiliaries (hydraulic, pneumatic, electric and battery thermal auxiliaries) energy consumption under real-world driving conditions.
2. It estimates the energy and battery size needs for a variety of public transit bus services including city, BRT, intercity, shuttle, and regional BEBs, while clearly highlighting their differences.
3. This is the first study that evaluates the battery sizing requirement for actual bus lines in the public bus transport network in the city of Paris, France.

2. Framework

This section presents the proposed framework for BEB battery sizing based on the precise assessment of the BEB real-world energy needs. The framework is composed of 3 steps as will be detailed in this section. The framework is summarized in Figure 1.

In the first step, the different BEB operating conditions are characterized based on the type of bus service by identifying the bus driving conditions, weather conditions, and level of passengers' occupancy. Besides, the bus schedule imposes several constraints on the adopted charging methods/infrastructure for each type of bus service [41].

The precise real-world BEB energy consumption is calculated in step two. The energy consumption is evaluated as function of the identified operating conditions. A comprehensive BEB energy model is developed in previous work by the authors [42]. The model includes the propulsion system, HVAC unit and all other auxiliaries (AUX) encountered in a BEB including the battery thermal management system (BTMS), hydraulic steering pump, pneumatic system air compressor, and other electric auxiliaries such as lighting, parking brakes, and doors.

Finally, the required battery size is determined in step three, based on the BEB energy consumption and available charging infrastructure. Since there is a direct relation between the bus battery size and its energy needs due to the battery additional weight and cooling needs that vary as function of the battery size, a correction feedback loop is implemented to correct the bus energy needs as function of the resulting battery size. The process is repeated until the battery size converges to a certain value, defined as less than 1% change in battery size for any 2 consecutive iterations.

The rest of this section explains in detail each step in the proposed framework.

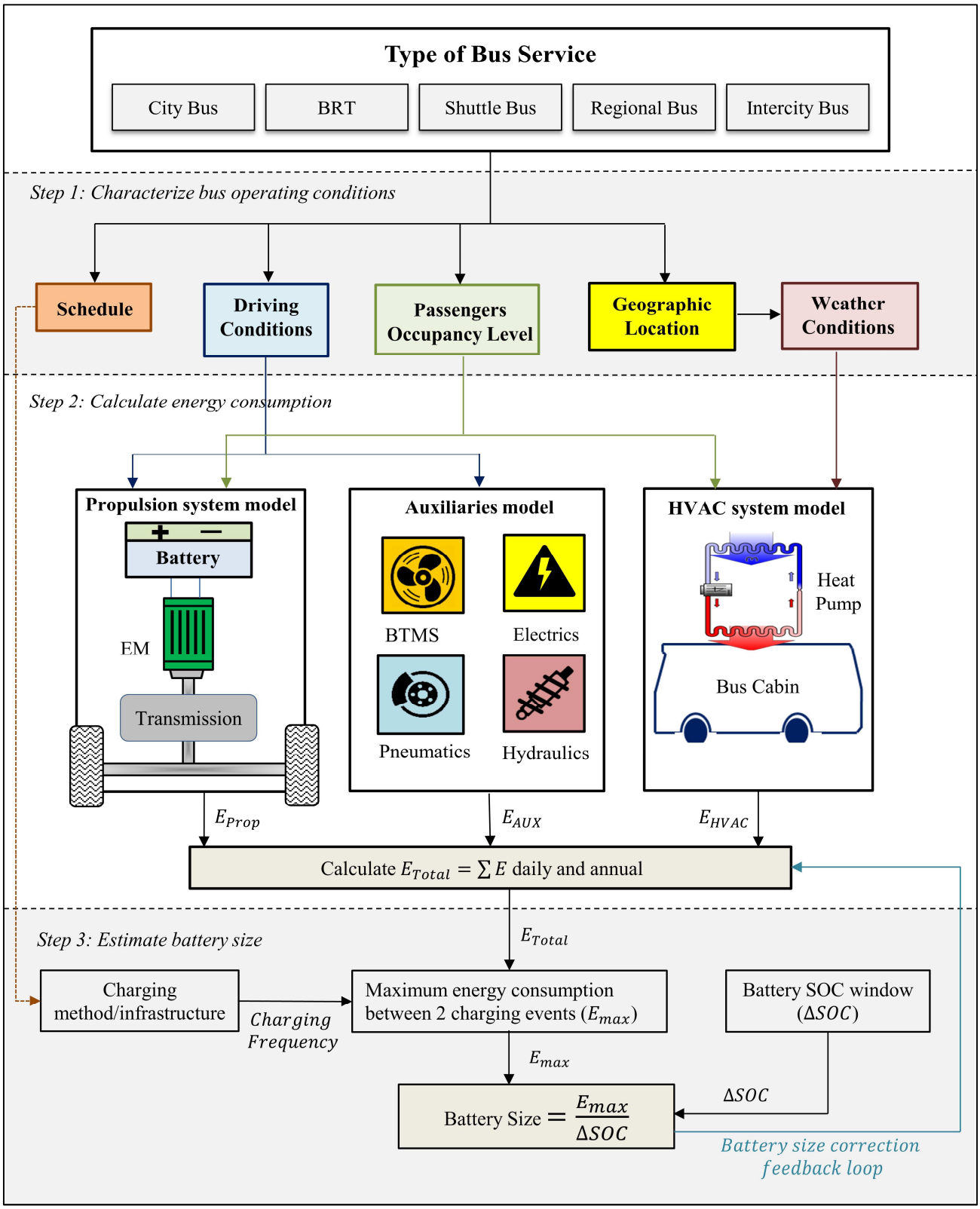

Figure 1: Framework for battery sizing

2.1 Characterize bus operating conditions

The bus operating conditions directly impact its energy consumption and affect the required battery sizing. These operating conditions can be categorized into (1) driving conditions, (2) passenger occupancy levels, and (3) weather conditions.

The operating conditions are identified for a certain bus trip, where a bus trip is defined as the bus operation between two locations, mainly a starting location and an end location. A trip could be defined as the bus operation between the depot and terminal station (one-way trip), depot-to-depot trip (round trip), or between any 2 stop stations along the bus route.

The driving conditions are characterized by the trip average speed, distance, duration, average deceleration, and the number of bus stops along the route. Each type of bus service encounters different driving conditions, and thus the energy needs vary across the different types of bus services. For instance, city buses normally operate along routes characterized by high traffic congestion resulting in low trip average speed and high average deceleration, whereas intercity buses operate on national/international routes, mainly highways, resulting in a high trip average speed. In addition, trip distance and duration vary among the different types of bus service where regional and intercity buses cover the longest distance during the day, and for long trip durations.

Passenger occupancy level in the bus has a significant impact on its energy consumption, mainly due to the passengers' weight and varying thermal comfort conditions inside the bus as function of passenger occupancy level. The level of passenger occupancy for city buses, BRT, and regional buses varies during the day, depending on the rush hour, and varies between weekdays and weekends. Shuttle buses, especially airport shuttles, mainly operate at their maximum level of passenger occupancy all day long. Intercity buses witness low occupancy during weekdays, which increases during weekends.

In addition, the weather conditions encountered during the bus trip have a direct impact on the BEB energy consumption, namely the HVAC unit energy consumption, however, they are independent of the type of bus service but rather depend on the geographic location. Weather conditions can be characterized by exterior temperature and solar flux intensity.

Table 1 summarizes the parameters which characterize the trip operating conditions.

Table 1: Summary of parameters characterizing trip operating conditions

	Parameter	Variable	**Unit**
Driving Conditions	Average Speed	V	km/h
	Distance	d	km
	Duration	Δt	h
	Average Deceleration	∂	m/s^2
	Number of Stops	ns	-
Weather	Temperature	T	$°C$

Conditions	Solar Flux Intensity	sf	W/m^2
Passenger Occupancy	Number of Passengers	np	-

For a given trip t_i, $\mathcal{C}_i$ is a vector of length 8 which contains the parameters characterizing the operating conditions of trip t_i as shown in equation (1), where N is the total number of trips during a given period.

$$\mathcal{C}_i = [V_i, d_i, \Delta t_i, \partial_i, ns_i, T_i, sf_i, np_i] \; \forall \; i \in \{1,2, \dots, N-1, N\} \tag{1}$$

In addition, the bus schedule has a direct impact on the battery sizing as it imposes constraints on the choice of the charging method. There are 3 identified stationary charging methods: (1) overnight charging, (2) end-line charging, and (3) opportunity charging [43]. Overnight charging takes place during the night when the buses are out of service. End-line charging takes place at both terminal stations of the bus line where the bus can be charged before its return trip, depending on its schedule. On the other hand, opportunity charging is conducted at stop stations along the bus line and for a very short time, mainly equivalent to the bus layover duration at the stop stations.

Each type of bus service can utilize a specific charging infrastructure depending on its driving conditions, in particular the number of stop stations along the bus route, and the bus schedule. All types of bus service can benefit from overnight charging as it takes place at the bus depot during the off-service hours. Regional and intercity buses benefit from long off-service hours during the night as their service is terminated earlier when compared to other types of bus service.

Mainly all types of bus service can be charged at their end-lines during the day if their schedules realize long-enough dwell times at the termini. City buses, BRT, and shuttle buses operate at a high frequency during the day which reduces the dwell time at the end-line affecting the practicality of end-line charging. On the other hand, intercity and regional buses operate at lower frequencies which makes end-line charging favorable for these types of bus service.

Opportunity charging depends on the number of stop stations along the bus route. City buses and BRT could utilize opportunity charging as they encounter a large number of stop stations during their operation, unlike shuttle and regional buses that encounter very few stop stations along their routes which makes opportunity charging hard to implement. As for intercity buses in general, opportunity charging is not possible as there are no stop stations along the bus route.

2.2 Calculate energy consumption

The precise real-world BEB energy consumption is calculated as function of the characterized operation conditions in step 2.1. A comprehensive BEB energy model is developed by the

authors for this sake using the Dymola software. The model consists of four main energy systems: (1) the battery which is the energy and power source, and three other energy systems that demand energy from the battery including (2) propulsion system, (3) HVAC unit, and (4) auxiliaries. The BEB considered in this study is the most common standard single deck 12-m rear-wheel-drive bus with a maximum capacity of 55 passengers. The model is described in detail in [42] and is validated for a city bus application (bus line number 21 in Paris) under typical real-world operating conditions. A schematic of the BEB configuration is presented in step 2 of Figure 1. The technology and specifications of the different BEB components are summarized in Table 2.

Table 2: Summary of bus configuration and component specifications

	Component	Technology	Parameters	Value
General	-	-	Gross vehicle weight	22 tonnes
			Max occupancy	55 passengers
			Mileage	f(battery size)
Battery	Battery pack	Lithium-ion	Cell energy capacity	14.6 Wh
			Cell charge capacity	4.3 Ah
			Cell mass	205 g
			Cell voltage	2.4 - 4.1 V
			Cell internal resistance	0.003 - 0.02 ohm
	Cooling unit	Air Cooling - Fan	Fan max airflow	1000 CFM
			Fan static pressure	100 Pa
Propulsion	Electric machine	3-phase AC inductive	Rated power	135 kW
			Rated torque	650 $N.m$
			Peak torque	1000 $N.m$
	Transmission		Reduction gear ratio	5.5
			Final drive ratio	5
			Efficiency	0.95
	Chassis		Glider Mass	11600 kg
			Frontal area	8.2 m^2
			Drag coefficient	0.55
			Rolling resistance coefficient	0.008
			Wheel radius	0.48 m
			Wheel inertia	20.52 $kg.m^2$

HVAC	Cabin		Thermal comfort (winter)	19-23 °*C*
			Thermal comfort (summer)	23- 27 °*C*
	Reversible HP	Single-stage VCC	Max heat rejection	20 *kW* (x2)
			Max heat extraction	15 *kW* (x2)
Auxiliaries	Pneumatic	Air compressor	Rated flow rate	4 *L/s*
			Rated power	2700 *W*
	Hydraulic	Steering pump	Power demand range	450-1000 *W*
	Electric	Doors	Power demand	90 *W*
		Parking brakes	Power demand	560 *W*
		Lighting system	Power demand	500 *W*
		Wipers	Power demand	500 *W*

- **Battery**

The BEB is equipped with a Lithium-ion battery, being the most common battery technology deployed in electrified vehicles [44]. The battery model is a coupled electro-thermal model that captures the electric and thermal dynamic behavior of the battery cells. A Rint equivalent-circuit quasi-static model is considered to estimate the battery state of charge (*SOC*), terminal voltage, and electric current using the battery empirical data, such as the battery cell open-circuit voltage and resistance as function of the battery SOC. The configuration of the battery cells (number of series and parallel modules) determines the battery pack energy capacity and voltage, where the latter should range between 600-800 *V* complying with the current state-of-the-art BEB [45]. The battery SOC operating window is recommended to be between 10-90 % [46] to reduce battery aging and prolong battery lifetime. In this study, a conservative battery depth of discharge at 80% is used to accommodate for battery capacity degradation with time.

To evaluate the additional energy consumption due to battery thermal management, a battery lumped thermal model is developed similar to [47], [48]. The model is a two-state model that estimates the battery cell core and surface temperatures, and internal heat generation resulting from the chemical reactions occurring at the battery electrodes. The battery is cooled using active-air cooling technology, utilizing a fan and an evaporator connected to the HVAC unit. The battery cooling unit consumes electric energy directly from the battery.

- **Propulsion system**

The BEB propulsion system consists of a single 3-phase AC induction electric machine (EM), a transmission unit, including a reduction gear and a final drive, and a braking system. The EM is modeled using an efficiency look-up map as function of its torque and rotational speed, in addition to inertial components to capture the EM dynamics. The EM can recover part of the bus kinetic energy during braking and thus operating as a generator in this case. The torque of the EM during traction and braking is controlled by a dedicated torque control unit (TCU) to meet the driver acceleration and braking demand and overcome the road resistive forces including aerodynamic drag force, rolling resistance force, and gravitational force.

The propulsion system is simulated at a variety of operating conditions as presented in [42]. The resulting propulsion system energy consumption is presented in Figure 2 as function of the trip average speed and the bus payload (wp). The bus payload is the sum of the passengers and luggage weight. Therefore, the energy consumption of the propulsion system (E_{Prop}) for a given trip, measured in kWh, is the product of the specific energy consumption ($\bar{E}_{Prop}$) extracted from Figure 2, multiplied by the trip distance as shown in equation (2).

$$E_{Prop} = \bar{E}_{Prop}(V, wp).d \tag{2}$$

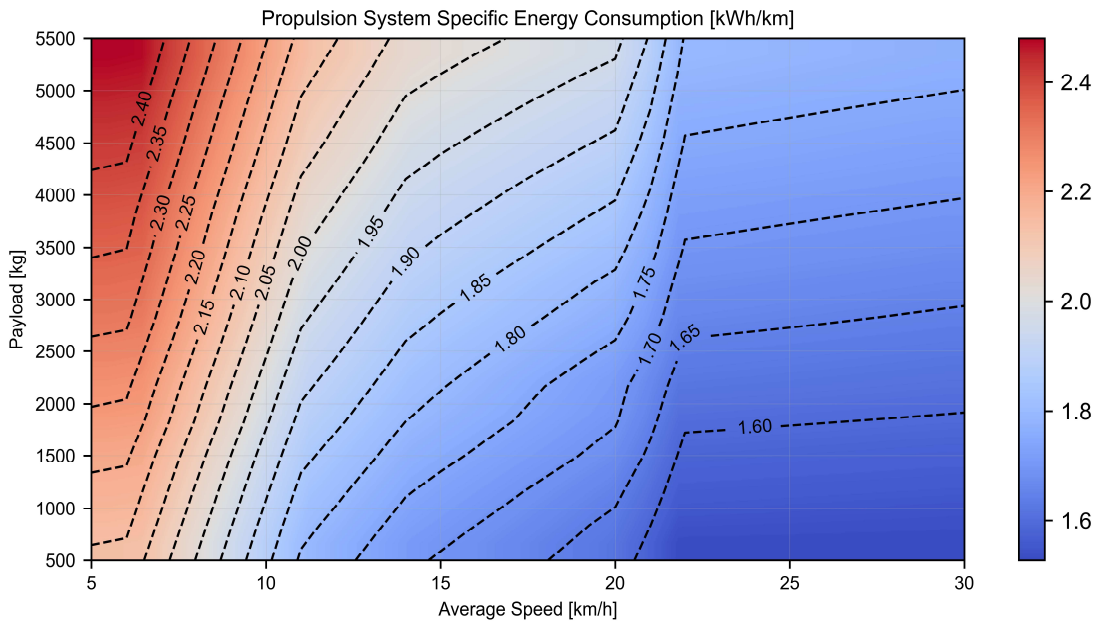

Figure 2: Propulsion system energy consumption

- **HVAC unit**

The HVAC unit should maintain the bus cabin thermal comfort needs in all weather conditions. In order to predict the required thermal energy needs, a bus cabin thermal model is developed consisting of multiple sub-models including cabin interior, walls, passengers, and internal materials. The dynamic heat transfer interactions among these sub-models are considered such as

convection between the walls and the exterior from one side and between the walls and cabin interior from the other side, conduction through walls, and incident, transmitted, and absorbed radiations through opaque and glazing walls. Passengers' heat rejection is considered in addition to radiation and convection between the cabin and its internal materials. Furthermore, heat losses due to door opening are considered as they disturb cabin thermal comfort conditions significantly [49]. The cabin model is presented in detail in [50].

Air source HP is the current state-of-the-art heating technology for EV due to their superior energy performance [51]. A HP operation can be reversed to consider cooling as well. Two reversible HP, each rated at 20 kW, are installed in the BEB to meet the cabin thermal comfort conditions. The HP operates on a single-stage vapor compression cycle (VCC) using refrigerant R1234yf. More details regarding the HVAC model can be found in [52].

The HVAC unit power demand (P_{HVAC}) is presented in Figure 3 as function of the external temperature and number of passengers occupying the bus. Figure 3 presents the average HVAC unit power demand which considers both transient and steady states, including the BTMS power demand. The BTMS power demand reaches 6 kW at extreme weather conditions. Other parameters also affect the HVAC unit power demand such as solar flux intensity and bus door opening during operation. For this sake, the additional HVAC unit power demand due to solar flux ($P_{HVAC-SF}$) is presented in Figure 4. Note that the negative values for $P_{HVAC-SF}$ below 20 $°C$ in Figure 4 indicate that solar flux reduces the required HVAC unit power during cold weather conditions. Finally, in order to consider the impact of bus door opening on the HVAC unit power demand, a correction factor (C_F) multiplies P_{HVAC}. Therefore, the energy consumption of the HVAC unit for a given trip (E_{HVAC}), measured in kWh, is presented in equation (3).

$$E_{HVAC} = (C_F . P_{HVAC}(T, np) + P_{HVAC-SF}(T, sf)). \Delta t \tag{3}$$

Δt is the trip duration measured in hours and C_F is expressed in equation (4) with α, β and γ are constants equal to (α = 0.0544), (β = 1.2305) and (γ = 0.6156) respectively, and R is the ratio of bus doors opening duration to trip total duration.

$$C_F = \alpha . R^2 + \beta . R + \gamma \tag{4}$$

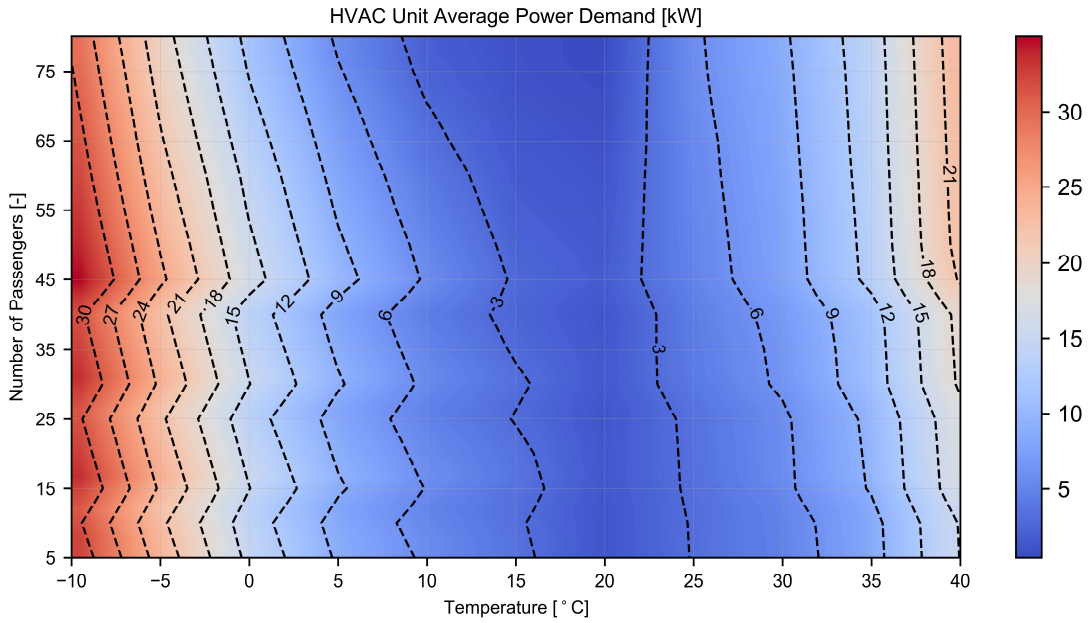

Figure 3: HVAC unit average power demand

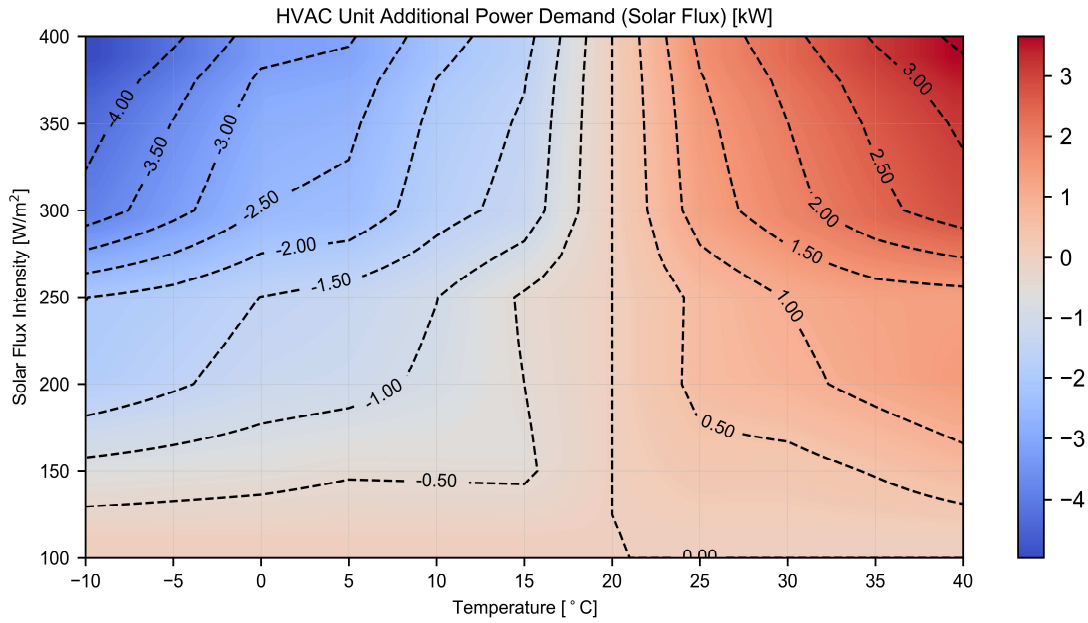

Figure 4: HVAC unit additional power demand due to solar flux

- **Auxiliaries**

BEB auxiliaries are essential for its operation and their energy consumption cannot be ignored. In addition to the BTMS, three types of auxiliary systems are identified in BEB: (1) pneumatic, (2) hydraulic, and (3) electric auxiliaries. The pneumatic AUX system operates the BEB service

brakes using. A dynamic pneumatic system model estimates the air compressor power demand during the bus operation. In addition, hydraulic auxiliaries include the steering pump and the bus suspension system. The steering pump power demand is modeled as a look-up as function of the bus speed whereas the suspension system power demand is estimated as function of the bus weight. Furthermore, electric auxiliaries are modeled as a constant power demand when actuated by the driver. These include lights, wipers, doors opening, and parking brakes. More details about the auxiliary model can be found in [42].

The pneumatic, electric, and hydraulic auxiliaries average power demand (P_{AUX}) is presented in Figure 5 as function of the trip average speed (V) and average decceleration (∂). Equation (5) expresses the auxiliaries energy consumption (E_{AUX}) measured in kWh.

$$E_{AUX} = P_{AUX}(V, \partial). \Delta t \tag{5}$$

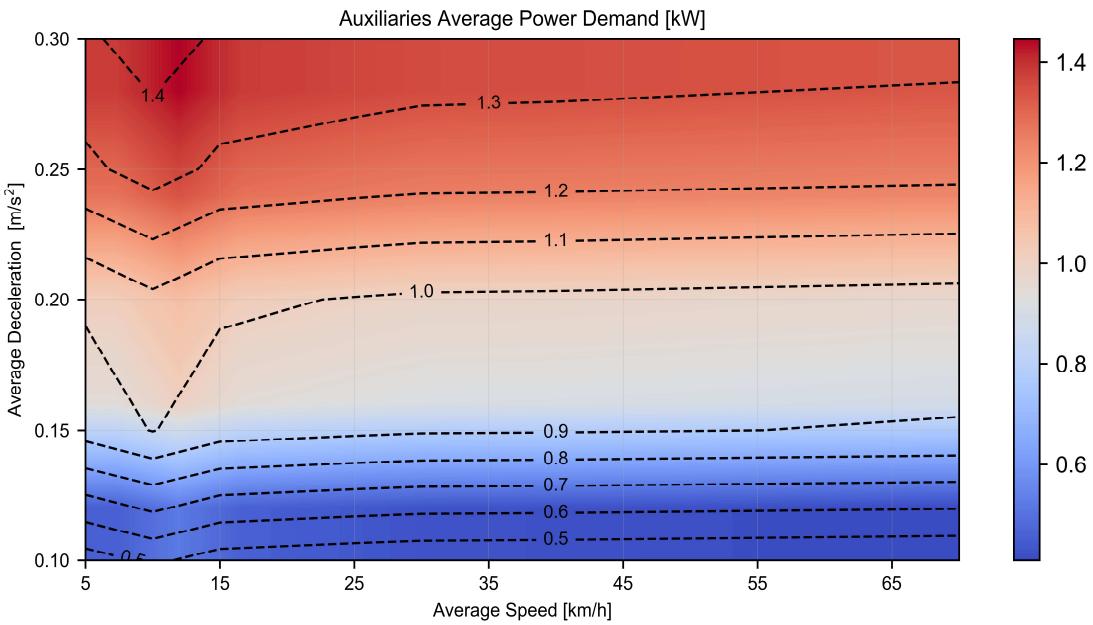

Figure 5: Auxiliaries average power demand

Finally, the total energy consumption for a trip t_i characterized by operating conditions $\mathcal{C}_i$ is the sum of the energy consumptions for each energy system as expressed in equation (6).

$$E_i(\mathcal{C}_i) = E_{Prop} + E_{HVAC} + E_{AUX} \tag{6}$$

2.3 Estimate battery size

The required battery size is dependent on the BEB energy consumption and the adopted charging infrastructure. The following assumptions are considered regarding the bus schedule:

- The bus makes the same number of trips N during each day throughout the year.

- The bus trip departure time is the same for each day throughout the year.

The annual energy consumption matrix (E) shows the bus energy consumption for any trip t_i for each day m as shown in equation (7) with M being the total number of bus operational days during the year.

$$E = \begin{bmatrix} E_1^1 & \dots & E_1^m & \dots & E_1^M \\ \vdots & & \vdots & & \vdots \\ E_i^1 & \dots & E_i^m & \dots & E_i^M \\ \vdots & & \vdots & & \vdots \\ E_N^1 & \dots & E_N^m & \dots & E_N^M \end{bmatrix} \quad \forall\, i \in \{1,2,\dots,N\} \wedge \forall\, m \in \{1,2,\dots,M\} \tag{7}$$

In order to ensure that the battery is capable of supplying the BEB energy needs at all operating conditions, battery sizing should consider the maximum required battery energy (E_{max}) before any trip start throughout the year as shown in equation **(8)**, and E_{Ci}^m is the charging energy used to charge the battery prior to trip i. It is worth mentioning that the cost-effectiveness of the BEB technology, which is highly driven by the battery size [53], is not within the scope of this paper and it will be considered in future studies, while the scope of this paper only covers the BEB technology analysis in terms of energy efficiency and battery size needs.

$$E_{max} = max\left(E_{i+1}^m + \sum_{i=0}^{i}(E_i^m - E_{Ci}^m)\right) \quad \forall\, i \in \{1,2,\dots,N\} \wedge \forall\, m \in \{1,2,\dots,M\} \tag{8}$$

The charging infrastructure determines the number of charging events before each trip. The value of E_{Ci}^m depends on the choice of charging infrastructure as shown in equation **(9)** with Δt_{Stop} being the bus stoppage time at the termini or any stop station, and P_C is the charging power. For overnight charging, the buses are not charged before their trip departure as charging only takes place at night. As for end-line and opportunity charging, E_C directly depends on the bus stoppage time and charging power. It can be assumed that the bus can charge its entire trip energy needs at its end-lines taking into consideration the recent development in the chargers' technology that realizes high charging power reaching 500 kW for bus applications [54]. On the contrary, a limited amount of energy could be charged at the stop stations during opportunity charging due to the very short bus stoppage time. That being said, the charging power at the stop stations should be defined for opportunity charging infrastructure.

$$\begin{cases} E_C = 0 & \text{for Overnight Charging} \\ E_C = f(\Delta t_{Stop}, P_C) & \text{Otherwise} \end{cases} \tag{9}$$

Then, the required battery size (K_b) is expressed in equation (10) with ΔSOC being the battery state of charge operating window. ΔSOC aims at reducing battery deep discharges that impact battery health at very low SOC.

$$K_b = \frac{E_{max}}{\Delta SOC} \tag{10}$$

The presented energy consumption and power demand maps in sub-section 2.2 of the methodology are developed for a 300-kWh battery. However, the battery size impacts the propulsion system energy consumption (Figure 2) due to its weight, which varies as function of the battery energy capacity. For example, the energy consumption of a BEB equipped with a 600-kWh is 7% more when compared to a BEB equipped with a 300-kWh battery according to our developed simulation models. Thus, a correction feedback loop is implemented to correct the bus energy needs as function of the resulting battery size. The bus energy consumption is calculated based on the new battery size (effectively the new bus weight). The process is repeated until the battery size converges to a certain value, defined as less than 1% change in battery size for any 2 consecutive iterations.

3. Case Study

3.1 Data Sources

A case study is presented in this section representing 5 different types of bus service operating in the city of Paris, France. Table 3 summarizes the main specifications of the bus routes considered in this study.

Table 3: Bus line route specifications

Type of Bus Service	Line Number/Operator	Starting Point	End Point	Roundtrip Distance [km]	# of Stops	Roundtrips per day
City Bus	21 - RATP	Saint-Ouen	Gentilly	22.2	42	6
BRT	393 - RATP	Thiais	Sucy Bonneuil	25.2	18	6
Shuttle Bus	OrlyBus	Orly Airport	Denfert Rochereau	24	3	8
Regional Bus	91.05 - Albatrans	Massy Gare	Evry Gare	40	10	5
Intercity Bus	FlixBus	Amiens	Paris	260	0	1

The operating conditions are identified for each type of bus service. The bus average speed per trip during the day is determined for weekdays, Saturdays, and Sundays, as traffic conditions highly vary during the day, and between weekdays and weekends. The driving conditions and passengers' occupancy data are collected using Google Maps-Python service, during the months of June-July 2020. Panel (a) of Figure 6 shows the daily average speed for city and regional buses

during weekdays (data for other types of bus service and during weekends are not presented to simplify the plots). Intercity buses are assumed to operate at a fixed average speed around 70 *km/h*.

Panel (b) of Figure 6 shows the daily average passenger occupancy for city and regional buses. This data is collected manually between May-June 2019. The following assumptions are made for other types of bus service:

- Shuttle buses (RATP - Orly Bus) are assumed to operate at maximum passengers' occupancy at all times as it is an airport shuttle bus.
- BRT is assumed to have a similar passenger occupancy profile to city buses, as both operate in the same geographic area and with similar schedules.
- Passengers' occupancy for the intercity bus (FlixBus – Amiens) is determined based on bus online booking history.

Panel (c) of Figure 6 shows the annual temperature occurrence in Paris [55], divided into 3 periods during the day: (1) morning, (2) noon, and (3) evening and the monthly average solar flux intensity [56] is presented in panel (d).

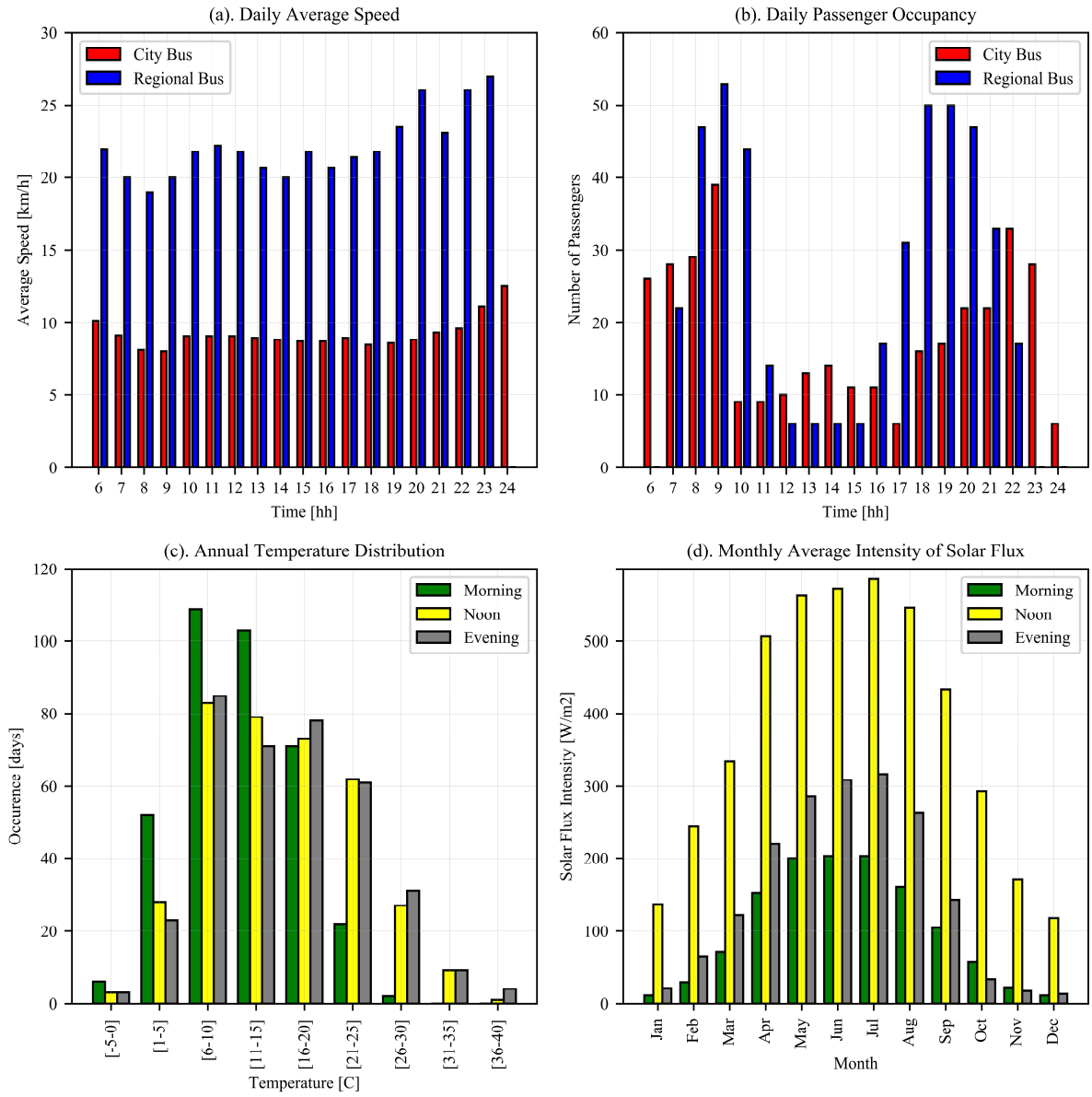

Figure 6: Bus operating conditions

In addition, based on the bus operating conditions presented in Table 3, especially the number of stops per bus round trip, some types of charging infrastructure might be more adequate as summarized in Table 4. Nonetheless, the analysis is conducted for all types of charging infrastructure for each type of bus service, except the combination of "opportunity charging - Intercity bus" as there are not stop stations along the intercity bus route, so opportunity charging is not possible.

Table 4: Summary of considered charging infrastructures and their adequacy for different types of bus service (+++ most adequate, + least adequate, NA: not applicable)

Type of Bus Service	Overnight Charging	End-Line Charging	Opportunity Charging
City	++	+	+++
BRT	++	+	+++
Shuttle	++	+	+
Regional	+++	++	+
Intercity	+++	+++	NA

With all the bus operating conditions being identified (refer to Table 1), these parameters are used to calculate the bus energy consumption using the developed maps (Figure 2 to Figure 5) and then estimate the required battery size for each type of bus service and for each charging infrastructure as will be presented in the results and discussion section.

3.2 Results and discussion

The energy needs for each type of bus service are evaluated under the operating conditions presented in Figure 6 and using the proposed framework. Figure 7 shows the BEB energy consumption for different types of bus service. The red scatters represent the mean energy consumption, and the error bars represent the minimum and maximum recorded energy consumption during the year.

City buses record the highest mean energy consumption around 3 *kWh/km* whereas shuttle and intercity buses record the lowest mean energy consumption around 2 *kWh/km*. This variation in the mean energy consumption across the different types of bus service is related to the operating conditions encountered by each bus, in specific driving conditions and passengers' occupancy, as all buses are subject to the same weather conditions since they operate in the same geographic/climatic area (Ile de France). City buses operate at the lowest average speed among all other buses which ranges between 8 – 12 *km/h*, mainly due to the higher levels of traffic encountered around and within city centers. This deteriorates the propulsion system efficiency, in particular the EM, resulting in increased energy consumption. On the contrary, intercity and shuttle buses record the highest average speeds, 26-30 *km/h* for the shuttle bus and 65 – 70 *km/h* for the intercity bus. This explains their lower energy consumption when compared to other buses. BRT and regional buses operate at 20-25 *km/h* average speeds. Although all buses are subject to similar weather conditions, buses operating at lower speeds suffer from prolonged trip duration per driven *km*, which effectively means that the HVAC unit operates for a longer duration per *km* further increasing the bus energy consumption.

In addition, the variation in energy consumption is different from one bus to the other. City buses witness a very broad distribution for energy consumption values as its energy consumption ranges from 2.4 *kWh/km* to 4.6 *kWh/km*, a 92% increase in energy consumption.

On the contrary, intercity buses witness the narrowest energy consumption distribution as it exclusively ranges from 2 to 2.15 *kWh/km*, less than an 8% increase. This behavior is also related to bus operating conditions. Buses that operate under highly varying operating conditions witness a broad distribution for energy consumption. City buses witness high variations in their driving conditions and passenger occupancy during the day whereas intercity buses mainly witness steady driving conditions as they operate on highways and international routes, in addition to the fact that their passenger occupancy is almost constant (pre-booking). High variations in driving conditions impact the bus energy consumption significantly as high levels of traffic congestion and frequent bus stop-and-start driving patterns affect the EM efficiency. In addition, the varying driving conditions result in different amounts of brake energy recovery during the bus trip, also impacting the bus energy consumption. Although BRT also operate around city centers, they are less sensitive to the variation in driving conditions as they operate on specific corridors for large portions of their routes and thus avoiding traffic congestion.

That being said, the energy consumption highly varies among the different types of bus service due to the different operating conditions they encounter, which makes it essential to consider the type of bus service when evaluating the bus energy needs.

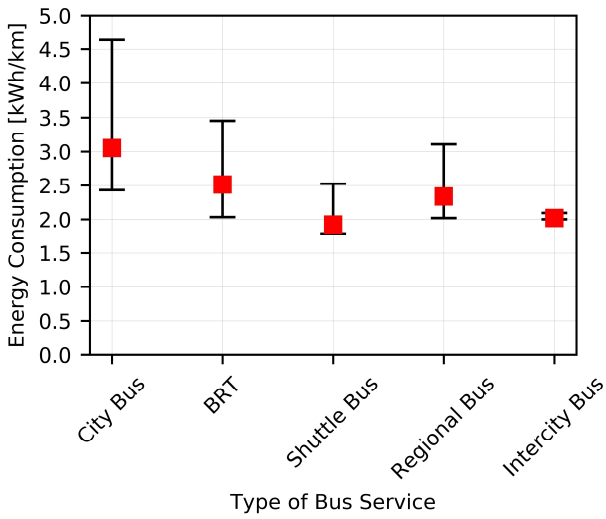

Figure 7: BEB energy consumption for different types of bus service

The proposed battery sizing framework is used to estimate the required battery size for each type of bus service under different charging infrastructures as presented in Figure 8. Panel (a) shows the required battery size under the overnight and end-line charging infrastructures. Note that end-line charging implies charging at the bus termini during the day and night as well (thus effectively it is overnight + end-line charging). The same explanation applies to opportunity charging.

For overnight charging, city buses require a 640-*kWh* battery to supply the entire BEB daily energy needs on a single charge during the night. Similar battery sizes are obtained for regional and intercity buses at 670 *kWh* and 680 *kWh* respectively, whereas BRT and shuttle buses require the smallest battery size during overnight charging at 550 *kWh* and 570 *kWh,* respectively.

Two factors drive the required bus battery size for overnight charging: (1) the bus energy consumption per driven *km* (presented in Figure 7), and (2) the total number of driven *km* during the day (refer to Table 3). Although intercity buses consume the least energy per *km* in comparison to other types of bus service, its required battery size is the largest due to the long distance it covers per day (260 *km* per day). Similarly, regional buses cover more than 200 *km* per day resulting in a large battery size. On the other hand, city buses cover the least *km* at 133 *km*, but their high energy consumption per *km* is yielding to their large battery size. BRT and shuttle buses experience moderate values for their energy consumption, and they cover 150-200 *km* per day, which explains their smaller battery sizes.

For end-line charging infrastructure, the required battery size is significantly reduced for all types of bus service. The required battery size ranges from 40 – 70 *kWh* for the different types of bus service, except for intercity buses as their required battery size is around 320 *kWh*. With end-line charging, there are multiple charging events during the day, mainly 2 charging events per bus round trip, and the total number of daily charging events depends on the schedule of each bus. City, BRT, shuttle, and regional buses can benefit from 10-16 charging events during the day, whereas intercity buses can only undergo a single charging event during the day. This explains the large required battery size for intercity buses under end-line charging infrastructure. Besides, the number of driven *km* between 2 consecutive charging events (the distance of a one-way trip in the case of end-line charging) directly drives the bus required battery size. All buses cover 10-20 *km* per one-way trip, whereas intercity buses cover 130 *km*.

On the other hand, for opportunity charging infrastructure, buses can benefit from multiple charging events at certain stop stations along their routes, in addition to the main charging events that take place at the end-lines or the depot. Opportunity charging is mainly very short, almost equivalent to the bus stoppage time at the station. It is assumed that buses can be charged for 20 seconds at their stop stations at 500 *kW*, being the most common fast-charging power rate implemented worldwide. Panel (b) of Figure 8 shows the required battery size for opportunity charging infrastructure for each type of bus service as function of the number of opportunity charging stations along the bus route. Mainly all buses show a linear reduction in battery size as the number of opportunity-charging stations increases. The required battery size for city bus and BRT could reach 33 *kWh* and 23 *kWh* respectively at a very high number of opportunity-charging stations (10 stations), which almost represent a 50% decrease in battery size when compared to end-line charging, assuming the power capacity of the battery is enough to meet the bus driving cycle needs.

Regional bus required battery size linearly decreases with the increase in opportunity-charging stations until it reaches a certain threshold at 8 opportunity chargers, with a required battery size

of 50 *kWh*, a 28% reduction in comparison to end-line charging. Unlike city bus and BRT, increasing the number of opportunity-charging stations beyond 8 does not affect the regional bus required battery size. This behavior is related to the location of the stop stations along the bus route. Stop stations for city buses and BRT are mainly placed equidistantly from each other (each 300-400 *m*), whereas the distance between two consecutive stop stations for regional buses is chaotic, as stop stations are mainly located at the entrance of small towns or industrial sites, and thus the minimum required battery size is driven by the longest segment along the bus route.

Shuttle bus can only benefit from 3 opportunity charging events as it only encounters three stop stations along its route, limiting the potential of battery size reduction. Intercity buses mainly do not encounter any stop station along their routes, and thus it is not possible to deploy opportunity charging stations.

Thus, the required battery size is directly driven by the type of bus service and the choice of the charging infrastructure. Significant reduction in battery size could be achieved when increasing the number of daily charging events (Opportunity charging > End-line charging > Overnight charging), however, this may increase the charging infrastructure cost which may overcome the reduction in the battery cost.

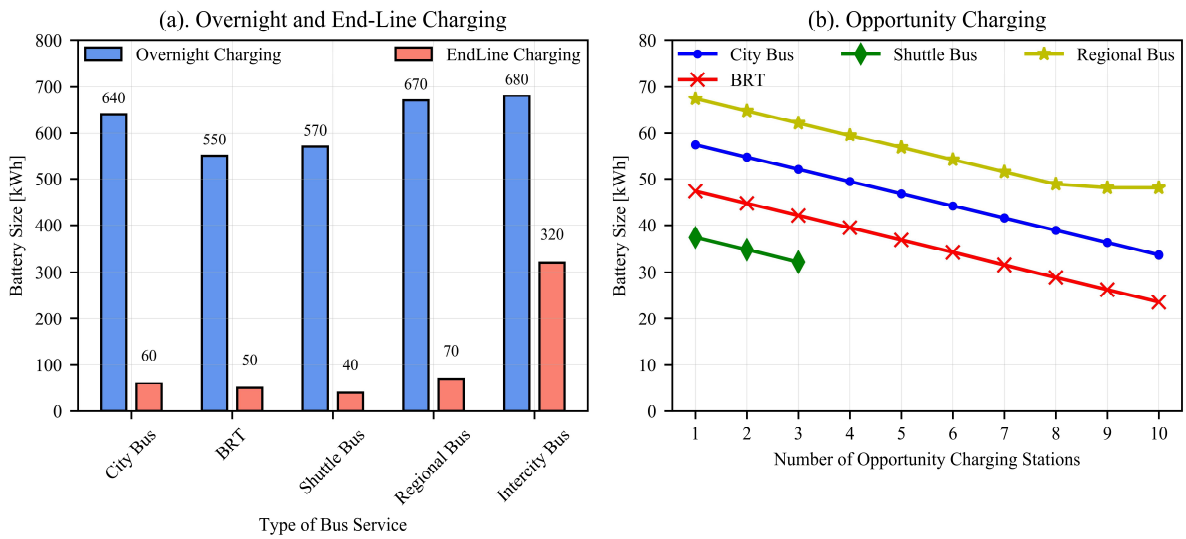

Figure 8: Required battery size for each type of bus service under different charging infrastructures

Batteries should be able to supply the BEB energy needs at all operating conditions, this urges bus operators to size the batteries with respect to the maximum BEB energy demand which is mainly encountered at extreme operating conditions (extreme cold/hot for temperatures below 0 °*C* or above 35 °*C*, very high traffic congestion for average speed below 10 *km/h*, and high passenger occupancy above 80%). However, these extreme conditions are not frequent, and thus for the majority of the bus trips, the batteries are oversized. An oversized battery yields a higher energy consumption due to the additional weight, not to mention the additional battery costs. The

rate of battery utilization per trip (R_u), indicates how much a battery is oversized. R_u is defined in equation (11) where E_i is the bus energy consumption between 2 consecutive charging events and K_b is the battery size. For example, E_i is energy consumption per day during overnight charging and the energy consumption per one-way trip during end-line charging.

$$R_{u,i} = \frac{E_i}{K_b . \Delta SOC} \tag{11}$$

Figure 9 shows the cumulative probability distribution function (CPDF) for rate of battery utilization for the different types of bus service during the overnight panel (a) and end-line charging infrastructures panel (b).

For the overnight charging infrastructure, 50% of the city bus trips require no more than 75% of the total battery energy, and 90% of the trips only require 85% of the total battery energy. For BRT, shuttle, and regional buses, higher utilization rates are observed where 50% of the trips require 84-87% of the total battery energy, and 90% of the trips require less than 93% of the battery energy. Intercity bus shows the highest utilization rate where almost 90% of its trips require 97% of the total battery energy. This high discrepancy in battery energy utilization rate among the different types of bus service (ranges from 75% to 97%) is directly related to the bus operating conditions. Buses that encounter high variations in their operating conditions witness the least rates of battery utilization whereas those who encounter minimal variations in operating conditions show a very high rate of battery utilization.

In other words, for city buses, the battery is oversized by 15% just to accommodate 10% of the bus trips.

In panel (b), lower utilization rates are observed for all types of bus service during end-line charging in comparison to overnight charging. 90% of the city and shuttle bus trips require no more than 68% of the total battery energy, thus the battery is oversized by 32% just to accommodate 10% of the bus trips. Similarly, 90% of regional bus and BRT trips do not require more than 77% and 81% of the total battery energy, respectively. Intercity bus attains high rate of battery utilization during end-line charging.

The lower observed utilization rates during end-line charging are related to the fact that batteries are sized based on the bus maximum energy needs between 2 consecutive full charging events. For end-line charging, the bus maximum energy needs correspond to the bus maximum energy needs per one-way trip, whereas for depot charging it is the bus maximum energy needs per day. When more trips are considered (energy needs per day), the discrepancy in the bus energy needs between 2 charging events becomes less, which explains the higher utilization rates observed during overnight charging.

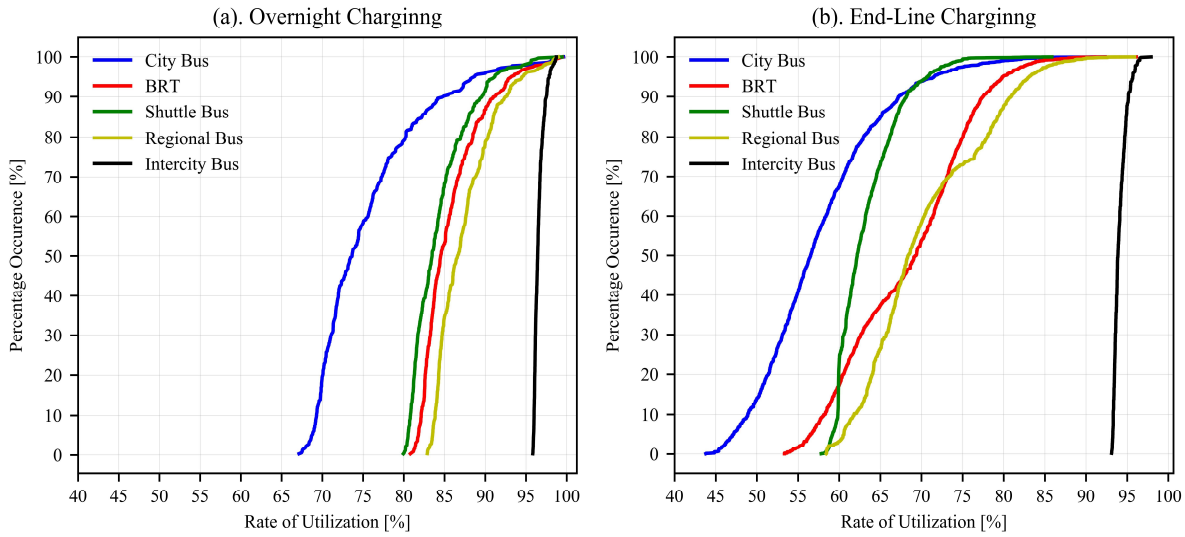

Figure 9: Cumulative probability distribution function for rate of battery utilization

Finally, Table 5 presents a summary of the main results highlighting the bus energy consumption for each type of bus service, the required battery size and rate of battery utilization as function of the different types of charging infrastructure.

Table 5: Summary of buses energy consumption, battery sizing needs, and rate of battery utilization as function of type of charging infrastructure

Service	Energy consumption (kWh/km)	Battery size (kWh)			Rate of battery utilization for 90% of annual trips	
		Overnight	End-line	Opportunity	Overnight	End-line
City	2.4 – 4.6	640	60	57 – 33	≤ 85%	≤ 68%
BRT	2 – 3.45	550	50	47 – 23	≤ 92%	≤ 77%
Shuttle	1.75 – 2.5	570	40	37 – 33	≤ 90%	≤ 68%
Regional	2 – 3.15	670	70	67 – 49	≤ 93%	≤ 81%
Intercity	2 – 2.15	680	320	NA	≤ 97%	≤ 95%

For buses operating at low rates of battery utilization for a large number of trips, there is room to reduce the battery size and effectively reduce its cost burden. For example, for the city bus during end-line charging, the battery is oversized by almost 32% just to accommodate 10% of the bus trips, which is around 20 days of operation during the year, mainly encountered in January due to the extremely low external temperature. If these heating needs could be supplied by heat sources other than the battery (diesel or methanol heaters for example), the battery size could significantly be reduced by 32%. Besides, other solution could be implemented to reduce the bus maximum energy needs, and effectively reduce the required battery size such as reducing the bus ridership capacity, utilizing a higher SOC window (low impact on battery aging if it is only implemented for a very low number of trips), and reducing the number of trips or replace the BEB with a diesel bus just for this 10% of the bus trips (20 days during the year).

This analysis provides important insights on the BEB annual energy performance and the possible room for reducing the battery size, which is driving the bus total costs.

4. Conclusion and Future Work

This paper presents a battery sizing framework for different types of electric bus services by assessing their real-world comprehensive energy consumption. The different types of bus service include city buses, BRT, shuttle buses, regional buses, and intercity buses. The proposed battery sizing framework is composed of three main steps: (1) the buses real-world operating conditions are identified all year round such as driving conditions, passenger occupancy, and weather conditions that vary all year round for the different types of bus service. (2) The annual bus energy consumption is evaluated based on the identified operating conditions using a comprehensive BEB energy model. (3) The bus battery size is estimated by considering its energy consumption and available charging infrastructure.

A case study is presented representing different types of bus service of interest while considering all stationary charging infrastructures available in Paris including overnight, end-line, and opportunity charging. The energy consumption of the buses shows a high sensitivity to the varying operating conditions they encounter during operation. City bus energy consumption ranges from 2.4-4.6 *kWh/km* whereas shuttle and intercity buses record an energy consumption between 2-2.5 *kWh/km*. City buses and BRT witness a broad distribution of their energy consumption, mainly driven by the varying driving conditions they encounter during the day, unlike intercity buses.

The required battery size for each bus type is evaluated for different charging infrastructures. Multiple charging events during the day could significantly reduce the bus required battery size depending on the bus operating conditions. Intercity buses require a battery size between 320 – 680 *kWh*, the largest battery size among all types of bus service, depending on the choice of the charging infrastructure. Other buses could be equipped with a reduced battery size reaching 50 *kWh* if accompanied by a high number of charging events during the day, which is the case in the opportunity charging infrastructure.

In addition, a statistical analysis is then conducted where the rate of battery utilization all year round is analyzed for the different types of bus service and different charging infrastructures. The analysis reveals that city buses suffer lower rates of battery utilization in comparison to other types of bus service where the battery is unnecessarily oversized to accommodate a few number of trips during the year. This shows that there is an opportunity to reduce the required battery size if the bus excessive energy needs are met during these rarely occurring conditions. Several technical recommendations are presented in this regard such as reducing the bus ridership capacity or the number of daily trips whenever these conditions are encountered.

The presented battery sizing framework is of great importance for bus operators as it provides valuable insights on the impact of bus operating conditions and the adopted charging

infrastructure on the required battery size. The described models were designed to be easily replicated and utilized and are easily adapted to any context by simply changing their inputs. Such analysis opens doors on bus fleets' electrification needs in terms of battery sizing and charging infrastructure at a public transport network level, for example at a city, province, or country level, where this modeling approach becomes more necessary.

In future work, the authors will consider examples of entire public transport network with fleets of BEB under different types of service and operating conditions which will help in determining the different types of required charging infrastructures, and the impact of bus fleet charging needs on the electric grid. Moreover, the energy analysis results presented in the case study motivate the investigation of another important issue for bus operators, namely the impact of bus high heating needs, which are needed only under rarely-occurring extreme cold weather conditions, on proper battery sizing for year-round operation. This will be further investigated in the future.

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6. Figures Caption Text:

Figure Number and Caption	Figure Size (Image Width)
Figure 1: Framework for battery sizing	2 Columns
Figure 2: Propulsion system energy consumption	2 Columns
Figure 3: HVAC unit average power demand	2 Columns
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Figure 6: Bus operating conditions	2 Columns
Figure 7: BEB energy consumption for different types of bus service	1 Column
Figure 8: Required battery size for each type of bus service under different charging infrastructures	2 Columns
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