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Deep Learning-Based Energy Management of an All-Electric City Bus With Wireless Power Transfer

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ABSTRACT Fuel cell-based hybrid electric vehicles are one of the most promising options to achieve zero-emission city buses. Efficient Energy Management (EM) plays a critical role to make such buses more efficient and practical. In this research, an available all-electric bus consisting of fuel cell (FC) and battery is considered and the efficiency of adding a Wireless Power Transfer (WPT) system to it is assessed. The proposed WPT system is only capable to receive energy in bus stations and use it to supply loads or charge the battery. To this end, the actual data of a city bus, its route and load profile were collected and utilized to ensure a realistic assessment. A full mathematical model of the energy system as well as the constraints governing the management issue is extracted and a Deep Deterministic Policy Gradient (DDPG) method is used to optimally manage the energy flows for the entire journey. All models are implemented in MATLAB software and the efficiency of the proposed system is investigated from economic and technical aspects. The results illustrate a high efficiency for the proposed WPT technique to be used in actual all-electric city buses.

INDEX TERMS Hybrid energy system, energy management, wireless power transfer, deep learning, and all-electric city bus.

NOMENCLATURE

Parameter	Definition
PARAMETERS OF THE BUS'S PHYSICAL MODEL	
a	Bus's acceleration
A	Bus's frontal area
c_d	Drag coefficient
f_a	Acceleration force
f_d	Drag force
f_g	Gravity force
f_r	Rotating force
f_t	Total force
g	Gravity acceleration
m	Mass
p	Tire's pressure
V	Bus's velocity
α	Road inclination
ρ	Air density
TECHNICAL PARAMETERS OF THE ENERGY SYSTEM	
E_B	Battery's energy capacity
E_{cha}^{max}	Maximum charging in an hour
E_{dis}^{max}	Maximum discharging in an hour
P_B	Batteries' nominal power
P_{FC}	FC's nominal power
P_{FC}^{max}	FC's maximum output power
P_{FC}^{min}	FC's minimum output power
α_m	Battery's over-discharge coefficient
α_M	Battery's over-charge coefficient
η_c	Battery's charging efficiency
η_d	Battery's discharging efficiency
η_{FC}^i	FC's efficiency in time i
η_{WPT}	WPT's efficiency
TECHNICAL PARAMETERS OF ENERGY MANAGEMENT	
a_1, a_2, a_3	FC' efficiency fitted equation's coefficients
A_t	Action space
Δt	Time sample length (h)
fdc	FC's dynamic coefficient
lt_B	Battery life time
lt_{FC}	FC life time
nc	Number of charging cycles
$P_{FC}^{(i)}$	FC's output power in time i
pf_{cdl}	Penalty function of charging/discharging limitation

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pf_{H2}	Penalty function of H_2 tank
pf_{SOC}	Penalty function of SOC
P^i_{Load}	Load's power in time i
$P^{(i)}_{WPT}$	WPT's output power (in time i)
P^i_{cha}	Charging power in time i
P^i_{dis}	Discharging power in time i
P_H	Hotel load
P_{B-L}	Provided power to supply the loads by the batteries
P_{F-B}	Provided power to charge the batteries by the FCs
P_{F-L}	Provided power to supply the loads by the FCs
P_{W-B}	Provided power to charge the batteries by the WPT
P_{W-L}	Provided power to supply the loads by the WPT
rH_2	Remained H_2
$SOC^{(i)}$	Battery's State of Charge (in time i)
S_t	State space

FINANCIAL PARAMETERS OF ENERGY MANAGEMENT

c_f	FC's cost coefficient
IC	Total investment cost
IC_B	Battery investment cost
IC_{FC}	FC investment cost
iic_B	Battery initial investment cost
iic_{FC}	FC initial investment cost
OC^i	Total operation cost in time i
OC^i_{FC}	FC operation cost in time i
OC^i_{WPT}	WPT operation cost in time i
ρ_{mid}	Power grid electricity cost in mid-peak period
ρ_{off}	Power grid electricity cost in off-peak period
ρ_{on}	Power grid electricity cost in on-peak period

I. INTRODUCTION

By considering the environmental and natural resource laws, hybrid energy systems based on FCs and batteries take advantage of their zero emissions, high-range navigation and reliable performance that have been regard as one of the most promising alternatives for the fossil fuel engines in the public transportation [1]. The hybrid electric vehicles' cost-effectiveness, reliability, performance and navigation range are highly reliant on the selection and sizing, integration, and management of the power resources [2].

In this regard, diverse energy system structures have been employed in the way of city buses electrification in the previous researches. As one of the first solutions, the utilization of batteries alongside diesel generators can be mentioned [3], [4], which cannot be categorized as zero-emission. To fully eliminate pollution, several energy systems such as: only battery [1], [5], FC and Battery [6], [7], FC, Battery and Super-capacitor [2], [8], Battery and WPT [9], [10], have been proposed.

Based on the proposed all-electric energy systems and their performance, buses with only batteries as their own energy sources suffer from the low-range of navigation [9]. To overcome the problem, the capacity of batteries should be increased which leads to weight increment and consequently higher consumption. One of the most suitable solutions to enhance the navigation range is FCs, however the low-dynamic response of FC must first be addressed [11]. In other words, FCs' output cannot follow the sudden changes in load profiles and must be utilized alongside a fast-response energy resource such as a battery or super-capacitor. Consequently, a hybrid energy system based on FC, battery and WPT would have a noticeable ability to offer a high-range of driving with an optimal weight and volume, and acceptable dynamic response for city buses.

On the other hand, a variety of methods have been developed to do the energy management issue in the available articles. In this regard, revolutionary algorithms [11], [12], dynamic programing [13], [14], fuzzy logic [8], model predictive control [4], [15], deep-learning methods [16]–[18], etc. have been applied on energy systems.

Beside the cost, the researchers in [1] tried to consider the life-cycle of the components to achieve an efficient power dispatch that not only decreases the operation costs, but also attempts to minimize any equipment-aging on the system. In [12], a full mathematical model of governing constraints is extracted to automatically adjust the search area and improve the search ability of the utilized evolutionary optimizer. Simultaneous EM and component-sizing techniques have been proposed in [11], [13], [18] to consider investments cost in the optimization procedure. The proposed EM method in [18] aims to find the best components' sizes and energy supply plan by considering both cost and reliability factors. In this regard, the summation of investment and operation costs and the Loss of Load Expectation index are taken as the main objectives. An expanded review of research in energy systems and EM techniques can be found in [19].

WPT technology, as a highly applicable option to increase the navigation range and reliability of buses, is of high interest for researchers to enhance all-electric buses. The feasibility of WPT technique usage in buses has been already assessed in technical point of view in [9], [10], [20]. In [9], [10], a comparison has been done between battery-based all-electric city buses with plug-in and WPT technologies from the viewpoints of investment and operation costs, and life-cycle, which both prove the applicability of the WPT. The authors in [20] propose a WPT system alongside diesel generator and battery which is able to receive energy while the bus is moving. To have an optimal energy system, the size of components is optimized in this research as well.

Based on previously proposed energy systems and energy management techniques, the necessity of developing a high-efficient EM method to assess the feasibility of WPT in a real cases FC-based city bus is extremely felt.

In this research, a new energy system structure is considered for an all-electric city bus. In the proposed system, FC is

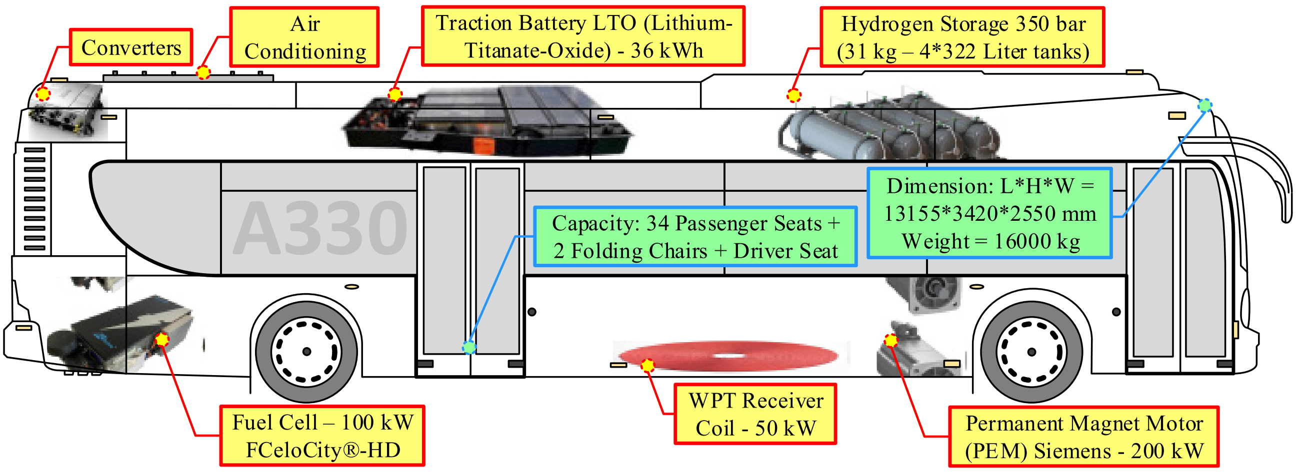

FIGURE 1. City bus and its energy system's specifications.

considered as the main energy resource which is accompanied by a battery-based energy storage unit and WPT technology as auxiliary energy sources to improve the whole system's performance and accessibility. The bus can be seen as a movable micro-grid, therefore, an optimal EM would have a considerable impact on enhancement of operation time and costs. Thus, as well as feasibility assessment of the WPT technology in all-electric city buses, the aim of this research is to present a cost effective and high performance EM method for the proposed hybrid energy system.

For this purpose, firstly, a WPT strategy is proposed with ability to receive energy from the city power grid only on bus stations. Moreover, the existing constraints are mathematically modeled in optimization search zone and an optimization method is utilized to find the optimal EM solution. To have a valid investigation, real data is used which includes the bus and route information, and the journey specifications (e.g. speed, elevation, etc.).

The considered journey for the bus includes a complete passing of the whole route and the waiting time to begin the next route which takes a total of 2 hours. In this regard, the EM problem is seen in a second form, all power flows among energy resources and loads are considered as optimization parameters and the optimization object is to minimize the total cost. Both investment and operation costs are seen in the objective function. Due to the high performance of machine learning techniques in particular, deep learning-based ones, the DDPG method [17] and [21] is used here to find the optimal EM solution.

In conclusion, the research's contributions can be expressed as below:

1- Assessment of the applicability of WPT system in an all-electric city bus;

2- Proposing a detailed mathematical model of the constraints to apply on the optimization method;

3- Introduction and implementation of an efficient EM method for the proposed bus's energy system;

4- Application of DDPG method to find the optimal solution.

The rest of the article is organized as follows. In next section, the specifications of the bus and its route, physical forces, and load profile is presented. The energy system's components and their features are expressed in section III. The constraints, cost function and optimization procedure of the proposed EM strategy is presented in section IV. The results and comparisons are available in section V. Section VI concludes the paper and highlights future work.

II. THE ALL-ELECTRIC BUS SPECIFICATION

As it has been mentioned, the purpose of this research is to implement an EM method on an all-electric city bus to investigate the feasibility of proposed WPT technique in this field. The available hybrid energy supply system here contains FC, battery, and WPT. All available loads in the bus (propulsion load and hotel loads) must be supplied by the mentioned resources efficiently. In this section, the bus and route's specifications, and the formulation of the load profile are presented.

A. BUS SPECIFICATIONS

The considered bus is a city bay, which is known as A330 [22] and in some parts of the world is used to transfer travelers. The energy section of the bus is currently supplied by FC and batteries and in this paper, beside those sources, the feasibility of a WPT technology which only is available in bus stations is assessed. The bus and its energy system's specification are illustrated in Fig. 1.

For the proposed EM method and energy system, two different states must be considered about the bus: "on road" and "in station" states. In the latter one, it is possible for the bus to wirelessly connect to the power network and receive electrical energy to either charge the battery or supply the loads. This wireless system can reduce the pressure on the batteries and FC and also decrease their size. In this work, the feasibility of adding WPT technology to the available electrical city bus is assessed, both technically and financially. The issue of component sizing and the impact of WPT on the reduction

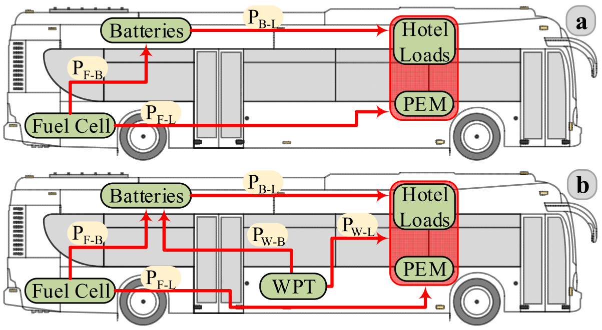

FIGURE 2. **The schematic of power paths: a) On road, b) In stations.**

of batteries and H_2 tanks capacities is going to be investigated in future.

So, the schematic views of the bus's energy resources and consumptions for both on road and in station states are respectively presented in Fig. 2a and 2b. According to the figure, the loads can be supplied by the provided power through the FC, battery pack and WPT and the battery can be charged by FC and wireless system.

B. ROUTE SPECIFICATIONS

The bus route used to investigate the proposed system, is a city bus line in Aarhus, Denmark. The line is known as Line-22 (Fig. 3), and starts from Aarhus bus station and after passing through 70 bus stops, it returns to its start point. It takes about 1 hour and 18 minutes for the bus to go through all the route and after that, it stays at the Arhus bus station for about 42 minutes to start over its journey again.

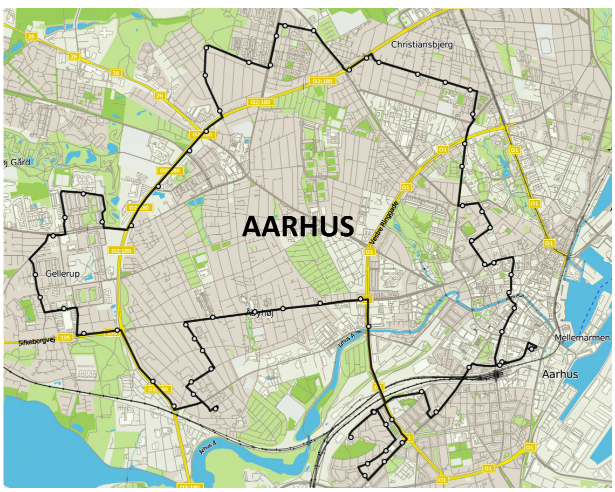

FIGURE 3. **The route specifications.**

The working hour of the line in usual conditions are from 6:15 a.m. to 22:30 p.m. and includes 2 buses. Therefore, each bus repeats the journey 8 times a day which must be considered in power consumption and storages to prevent any lack of power in batteries or H_2 in tanks.

C. POWER PROFILE

As it has been said, a whole journey of the bus (including driving and waiting periods) takes 2 hours. So, all the bus's

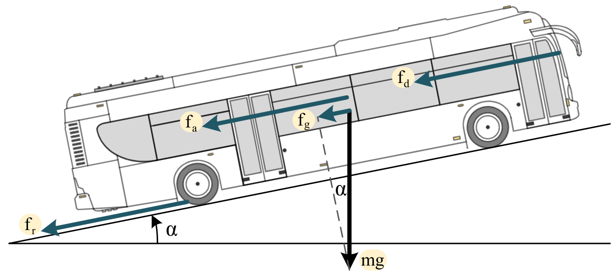

FIGURE 4. **Physical arrangement to model and design the traction system.**

supply loads (propulsion and hotel loads) must be calculated for that time cycle. It should be mentioned that, due to the low dynamic response of the FCs and necessity to see the sudden changes in the loads, the power profile is going to be prepared per second. For that, it is required to investigate a physical model of the bus (Fig. 4). Here, all the shown forces are defined and their formulations are presented.

1) ACCELERATION FORCE

This force is defined as the required power to change the bus's speed and is calculated as follow:

$$f_a = ma \tag{1}$$

2) GRAVITY FORCE

Only the horizontal component of the gravity has impact on the power profile of the bus. So, based on Fig. 4 and considering the slope degree, the force can be formulated as:

$$f_g = mg \sin \alpha \tag{2}$$

3) ROTATING RESISTANCE

This force is a consequence of reaction between tires and the road surface, and can be calculated for each tire as follow:

$$\begin{cases} f_r = \left(0.005 + \left({}^{1}/_{p}\right)\left(0.01 + 0.0095\left({}^{V}/_{100}\right)^{2}\right)\right) \\ *m*g \quad V \neq 0 \\ f_r = 0 \quad V = 0 \end{cases} \tag{3}$$

4) DRAG FORCE

Although this type of force has a relatively lower value in comparison to acceleration and gravity forces, but to have a more accurate model of the system, it is considered as below:

$$f_d = \frac{1}{2}\rho A c_d V^2 \tag{4}$$

Therefore, the total applied physical force on the bus is equal to:

$$f_t = f_a + f_g + f_r + f_d \tag{5}$$

Beside these mentioned physical forces, the hotel load must be considered in the power profile of the bus. This load includes Air conditioning, lighting, speakers, etc. As these loads usually do not have a considerable change during a journey, a constant value (P_H) is considered for them.

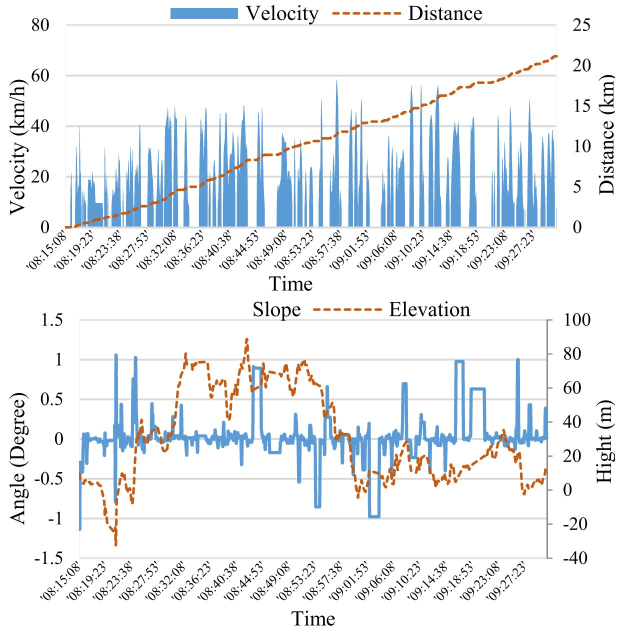

FIGURE 5. **The bus's a) velocity and distance, b) slope and elevation.**

As it can be seen in the presented equations, to produce a second based load profile, it is necessary to have the bus velocity and slope angle in every second of the journey. To achieve that, the geographical information of the bus is collected by a GPS recorder and used to calculate required data. Fig. 5 illustrates the collected and computed velocity and slope of the bus and based on them and equations (1) to (5), the power profile of the problem is calculated and presented in Fig. 6.

III. THE ENERGY SYSTEM AND CONSIDERATIONS

According to section II, the available energy resources in the considered energy system are FC, battery, and WPT. In the bus energy system, all energy sources and loads (propulsion and Hotel load) are connected to a DC link. In order to connect the components and the DC link together, electronic converters are utilized which are operates by a control system. The power sources' specifications are presented in the rest of this section.

A. FUEL CELL

FCs have an allowed operation range and in order to obtain the minimum and maximum power output of the utilized FC (HD7-100), its efficiency to the percentage of power output diagram is illustrated in Fig. 7. It can be seen that the output power of the FC should be between 10 to 100 percent of its nominal power output, which are equal to 10 to 100 kW.

In order to see the impact of diverse FC efficiency in different power outputs in the EM problem, a second order equation is fitted on the efficiency diagram:

$$\eta_{FC}^{i} = a_1 {P_{FC}^{i}}^2 + a_2 P_{FC}^{i} + a_3 \tag{6}$$

As it has been mentioned before, FCs cannot rapidly respond to the sudden changes in the loads, due to their low dynamic response [23]. So, it is necessary to join them with another resource of energy with ability to apply a rapid change to its output (batteries in this case).

Based on Fig. 6, it can be seen that the load is presented for each second, so, it means that any sudden change can be considered in the EM problem. Therefore, to account for the dynamic response of FCs, the below equation is used:

$$P_{\mathrm{FC}}^{i-1} - fdc \leq P_{\mathrm{FC}}^{i} \leq P_{\mathrm{FC}}^{i-1} + fdc \tag{7}$$

The other subject that should be considered in an EM problem to effectually investigate the applicability of suggested method is costs. In this paper, two kinds of costs are considered for each piece of equipment: ''Operation Cost'' and ''Investment Cost''. For FCs, the operation cost in each time can be modeled as a constant coefficient (related to the H_2 price) in the FC's input power. So, it can be presented as:

$$OC_{FC}^{i} = c_f * \left(P_{FC}^{i} \big/ \eta_{FC}^{i} \right) \tag{8}$$

As the operation cost is calculated only for a 2-hours journey, the investment cost must be obtained in the same form. So, the total initial investment cost is divided to its hourly life time and then multiplied in 2 for having a 2-hour time consideration. Thus, this cost is modeled as:

$$IC_{\mathrm{FC}} = \frac{(P_{FC} * iic_{\mathrm{FC}}) * 2}{lt_{\mathrm{FC}}} \tag{9}$$

To have an accurate model of the FCs, the capacity and consumption rate of H_2 must be considered in the problem, too.

B. BATTERY

Due to the high investment cost of the batteries, in order to increase their life time, some considerations must be strictly taken into account during the EM. Firstly, to avoid warming up the batteries that decrease their life time [24], the transferred power to and from batteries in a specific time (e.g. in an hour) must be limited. Consequently, the hourly maximum charging and discharging concepts are defined and applied on the problem.

Moreover, the over-charging and over-discharging must be avoided to prevent any additional damage to batteries. As a result, battery's State of Charge (SOC) must be kept in a safe range by the presented equation in follow:

$$\alpha_m * E_B \leq SOC \leq \alpha_M * E_B \tag{10}$$

Beside the life time related limitations, there is another consideration in regard to batteries which is their charging and discharging efficiency. This issue can be easily implemented on the model by:

$$SOC^{i} = SOC^{i-1} + \eta_c P_{Cha}^{i-1} - {}^{1}\!/_{\eta_d} P_{Dis}^{i-1} \tag{11}$$

As the same as FCs, it is required to model both operational and investment cost of batteries in the problem. But, by considering the fact that batteries do not use any resources to provide energy and they just store the provided energies,

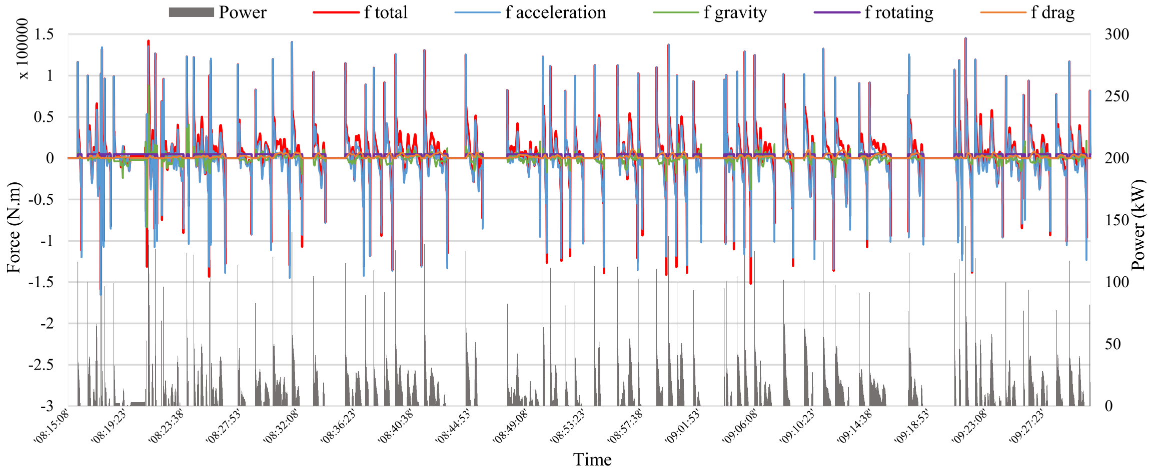

FIGURE 6. The variation of mechanical forces and the load profile.

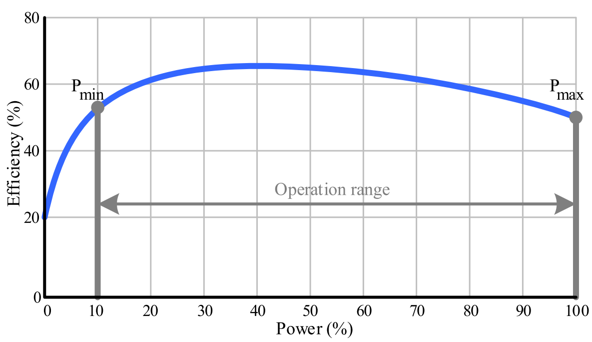

FIGURE 7. Efficiency to the percentage of output power (HD7-100).

the cost of their output power is already paid. Of course their losses would apply some costs on the system, but the impact of this phenomenon is already met in equation (11).

The battery investment cost can be calculated like FCs with a small difference. In FCs, their life time is in the form of time, but for batteries, it is in the form of charge or discharge cycles [11] and [18]. Thus, by having the number of the cycles, batteries investment cost can be calculated as below:

$$IC_{\mathrm{B}} = \frac{(E_B * iic_{\mathrm{B}}) * nc}{lt_{\mathrm{B}}} \tag{12}$$

Also, during energy management, it should be considered to use the batteries capacity in a way that they will be ready to work for the next journeys in the same day.

C. WIRELESS POWER TRANSFER

The WPT system transfer the power from the city power grid to the bus by the induction coupling. The system includes inverters, rectifiers, regulators and transmitter and receiver coils, all of which must be considered in the total efficiency of the WPT.

Due to the different electricity cost of city power network in different hours, the operation cost of WPT is dependent on the working hour. So, its operation cost can be defined as:

$$OC^{i}_{\mathrm{WPT}} = \begin{cases} \rho_{on} * \left(P^{i}_{WC}/\eta_{WC}\right) & i \in [7, 10) \cup [18, 20) \\ \rho_{mid} * \left(P^{i}_{WC}/\eta_{WC}\right) & i \in [6, 7) \cup [10, 18) \cup [20, 22) \\ \rho_{off} * \left(P^{i}_{WC}/\eta_{WC}\right) & i \in [22, 6) \end{cases} \tag{13}$$

Infrastructure associated with WPT at the stations have a very long lifetime and can be shared among buses and intersecting bus routes. Distributing the investment cost of WPT among these buses, the cost per journey is relatively low compared to other costs and has not been accounted for here.

IV. ENERGY MANAGEMENT

The main goal of the proposed EM strategy in this research is to optimally adjust the provided powers by the FC, battery and WPT and stored power in battery in each second for a whole journey (2 hours). The target of the optimization is the lowest cost in a way that loads and all constraints are satisfied. In this regard, the DDPG method is used to minimize the cost function. Here, the modeling of constraints and cost function, and also a brief explanation of the DDPG method is presented.

A. CONSTRAINTS

Due to the diversity of the energy resources and loads, high complexity of the energy system and also different bus operation modes, the EM issue faces a lot of constraints that must be met. All of these constraints for three different working mode (“Long stop mode”, “Driving mode” and “Short stop mode”) are modeled by the form of equations (14) to (25) that are illustrated in Table 1. the related brief explanations regarding to them are presented here.

TABLE 1. Constraints modeling.

Situation	Constraints' model	#
Long stop mode	$P^i_{W-L} = \min\left[P_{WPT}, P^i_{Load}\right]$	(14)
	$P^i_{B-L} = P^i_{Load} - P^i_{W-L}$	(15)
	$P^i_{W-B} = \min\left[\left(P_{WPT} - P^i_{W-L}\right), \left(\left(\alpha_M * E_B\right) - \left(SOC^{i-1} - P^i_{B-L} * \Delta t\right)\right) / \Delta t\right]$	(16)
Driving mode	$\max\left[0, P^i_{Load} - P_B\right] \leq P^i_{F-L} \leq \min\left[P^{\max}_{FC}, \left(P^{i-1}_{F-L} + P^{i-1}_{F-B} + fdc\right), P^i_{Load}\right]$	(17)
	$P^i_{B-L} = P^i_{Load} - P^i_{F-L}$	(18)
	$\max\left[0, \left(P^{\min}_{FC} - P^i_{F-L}\right), \left(\left(\alpha_m * E_B\right) - \left(SOC^{i-1} - P^i_{B-L} * \Delta t\right)\right) / \Delta t, \left(\left(P^{i-1}_{F-L} + P^{i-1}_{F-B} - P^i_{F-L}\right) - fdc\right)\right] \leq P^i_{F-B} \leq$ $\min\left[\left(\left(\alpha_M * E_B\right) - \left(SOC^{i-1} - P^i_{B-L} * \Delta t\right)\right) / \Delta t, \left(P^{i-1}_{F-L} + P^{i-1}_{F-B} - P^i_{F-L} + fdc\right), P^{\max}_{FC}\right]$	(19)
	$P^i_{W-L} = P^i_{W-B} = 0$	(20)
Short stop mode	$P^i_{W-L} = 0$	(21)
	$\max\left[0, P^i_{Load} - P_B\right] \leq P^i_{F-L} \leq \min\left[P^{\max}_{FC}, \left(P^{i-1}_{F-L} + P^{i-1}_{F-B} + fdc\right), P^i_{Load}\right]$	(22)
	$P^i_{B-L} = P^i_{Load} - P^i_{F-L}$	(23)
	$0 \leq P^i_{W-B} \leq \min\left[P_{WPT}, \left(\left(\alpha_m * E_B\right) - \left(SOC^{i-1} - P^i_{B-L} * \Delta t\right)\right) / \Delta t\right]$	(24)
	$\max\left[0, \left(P^{\min}_{FC} - P^i_{F-L}\right), \left(\left(\alpha_m * E_B\right) - \left(SOC^{i-1} + \left(P^i_{W-B} - P^i_{B-L}\right) * \Delta t\right)\right) / \Delta t, \left(\left(P^{i-1}_{F-L} + P^{i-1}_{F-B} - P^i_{F-L}\right) - fdc\right)\right] \leq P^i_{F-B} \leq$ $\min\left[\left(\left(\alpha_M * E_B\right) - \left(SOC^{i-1} + \left(P^i_{W-B} - P^i_{B-L}\right) * \Delta t\right)\right) / \Delta t, \left(P^{i-1}_{F-L} + P^{i-1}_{F-B} - P^i_{F-L} + fdc\right), P^{\max}_{FC}\right]$	(25)

1) LOAD SUPPLY

This constraint guarantees that the loads are satisfied any time. This goal is modeled by equations (15), (18) and (23).

2) SOC RANGE

This constraint prevents over-charging and over-discharging by using α_m and α_M in equations (16), (19), (24) and (25).

3) FC AND WPT'S OPERATION RANGE

In order to maintain the FC's output in its operation range, $P^{\min}_{FC}$ and $P^{\max}_{FC}$ are defined and used in equations (17), (19), (22) and (25). The same procedure is adopted for WPT system by P_{WPT} in equations (14), (16) and (24).

4) FUEL CELL'S DYNAMIC

As it has been said before, FCs have a low dynamic that makes them unable to follow the fast changes in the loads required in city bus routes. This feature is applied in equations (17), (19), (22) and (25) by fdc, as the allowed amount of change in the FC's output in each second.

5) OTHERS

There are some other constraints such as: H_2 usage (by pf_{H2}), batteries charging and discharging limitations (by pf_{cdl}) and SOC equality at the beginning and ending points (by pf_{soc}). These are modeled in the cost function as penalties in form of a high-value constant if "the total used H_2 is higher than the considered amount for a journey", "charged(/discharged) energy in any hour is higher than E^{max}_{cha} ($/E^{max}_{dis}$)" or if "in each time, SOC is out of the allowed range".

B. COST FUNCTION

The aim of EM is to minimize the costs. Therefore, the cost function can be modeled in form of minimizing the summation of operation cost, investment cost and penalty functions as it is presented in (26). The components of operation cost and investment cost are illustrated in (27) and (28), respectively. As it is clear in (27), due to the different resources in driving and stop modes, their operation costs is defined separately. It should be mentioned that, because of the uniformity of loads and energy costs during the long stop mode, this period of time is not seen in the optimization and its cost is simply calculated and added to the optimal obtained costs of other modes.

$$\min\left(\sum_{i}^{2-hours}\left(OC^i\right) + IC + (pf_{H2} + pf_{cdl} + pf_{SOC})\right) \quad (26)$$

$$OC^i = \begin{cases} \mathrm{OC^i_{FC}} & \text{Driving mode} \\ \mathrm{OC^i_{FC}+OC^i_{WPT}} & \text{Short stop mode} \end{cases} \quad (27)$$

$$IC = IC_{FC} + IC_B \quad (28)$$

C. OPTIMIZATION

In order to optimize the bus energy management, DDPG method is utilized in this paper as a reinforcement learning technique that combines both Q-learning and Policy gradients in a continuous problem. From the reinforcement learning aspect, the deterministic policy gradient is more suitable for designing an energy management system of electric buses because it can be estimated with higher efficiency in comparison to the usual stochastic policy gradient [17]. In order

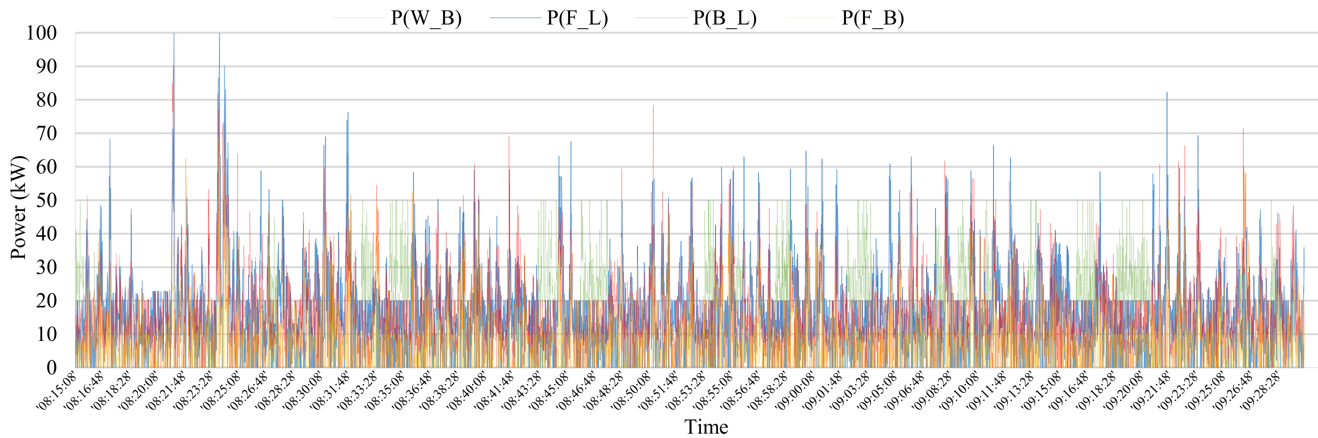

FIGURE 8. Optimal power flows.

to utilize the reinforcement learning in the optimization of all-electric bus EM problem, the Markov Decision Process (MDP) [25] is implemented to formulate the system's control operation.

A more detailed explanation of the proposed DDPG optimization method in an EM problem used here can be found in [21]. The important aspects to mention here are the system's State and Action spaces. State space is a collection of all possible states that the system can assume and should be able to reflect its information as is easily obtainable. By considering the two available energy storages (remained H_2 and batteries *SOC*) and the three energy resources in the bus, the selected state space is chosen as (29), which can easily and completely describe the system's state. In addition, action state is a collected set of possible actions that can cause a transition from one state to another one. Therefore, a set of all power paths in the system (30) is chosen as the actions.

$$S_t = \{SOC, rH_2, P_{FC}, P_B, P_{WPT}\} \tag{29}$$

$$A_t = \left\{P^i_{F-L}, P^i_{F-B}, P^i_{B-L}, P^i_{W-L}, P^i_{W-B}\right\} \tag{30}$$

V. NUMERICAL RESULTS

MATLAB R2020a software is used to implement the proposed EM strategy on the city bus. The value of all required parameters in this regard is shown in Table 2.

As it has been told that, the EM is seen in second form for a 2 hour journey which include of 1 hour and 18 minutes of moving and 42 minutes of waiting in the main station to start the next round. By considering the uniformity of electricity cost and load in the latter condition, the optimization of power resources in this 42 minutes is not going to have any impact on the total optimization. So, the EM optimization is only done for the driving and short stop modes. The values of all optimization parameters (power flows) are presented in Fig. 8 in seconds.

As it is clear from Fig. 2, the loads can be supplied by the FC, Battery and WPT. Fig. 9 illustrates the power flows from these three resources to the loads in addition to the load profile. The figure clearly shows that the loads are satisfied by the power sources in each second sufficiently; therefore, the proposed optimization suitably pleased the "Load supply" constraint.

TABLE 2. System's parameters.

Equipment	Parameter	Value
FC	P_{FC}^{max}	100 kW
	P_{FC}^{min}	10 kW
	c_f	0.16 \$/kWh
	iic_{FC}	40 \$/kW
	lt_{FC}	40,000 hours
	(a_1, a_2, a_3)	(-0.58, 0.58, 0.49)
Battery	P_B	72 kW
	E_B	36 kWh
	$E_{Cha}^{max} = 0.5 * E_B$	18 kWh
	$E_{Dis}^{max} = -0.5 * E_B$	-18 kWh
	α_m	0.3
	α_M	0.8
	η_c	85%
	η_d	100%
	iic_{b}	17.8 \$/kWh
	lt_{b}	1460 cycles
WPT	P_{WPT}	50 kW
	ρ_{on}	0.32 \$/kWh
	ρ_{mid}	0.16 \$/kWh
	ρ_{off}	0.07 \$/kWh
	η_{WPT}	85%

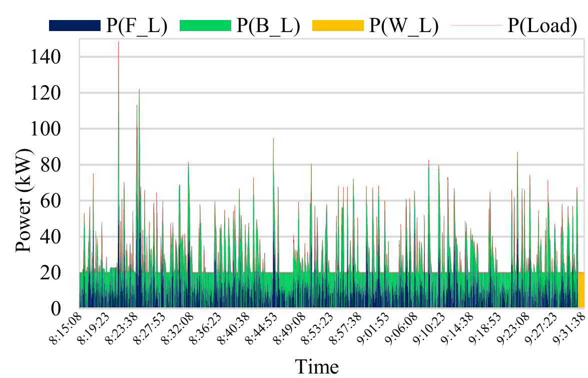

FIGURE 9. The bus's load profile and the share of each supplier.

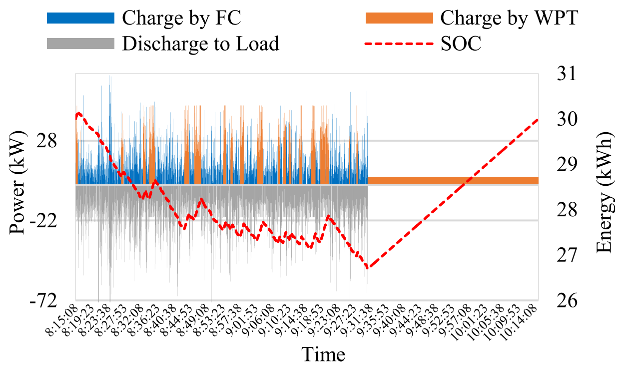

FIGURE 10. Power flows to and from the battery, and battery's SOC.

Also, the power flows to and from the battery as well as the battery's SOC is demonstrated in Fig. 10. Based on the figure, all "SOC range", "batteries charging and discharging limitations", and "SOC equality at the beginning and ending points" constraints are adequately satisfied by the proposed optimization solution.

In order to assess the feasibility and applicability of the proposed WPT technology in the energy system, a comparison is provided by two other scenarios:

1- The available all-electric energy system on the mentioned bus which includes FC and Battery (to assess the feasibility);

2- A common hybrid diesel engine and battery energy storage system (to assess the applicability).

The total costs which includes both investment and operation costs in a 2-hour period are presented in Table 3 for the proposed energy system and two other scenarios.

TABLE 3. Comparison of total cost for different energy systems.

Equipment	Total cost ($/journey)
Electric bus with WPT	**~ 8.75**
Electric bus without WPT	~ 8.62
Diesel engine + battery	~ 7.54

The first scenario only use plug-in technique to charge the battery, which compared to WPT is slightly cheaper due to the WPT's losses; so, the first scenario would require lower costs in this regard. But on the other hand, the utilization of WPT reduces the FC usage which is usually more expensive than the power grid price. It can be seen in the results that, the total cost of proposed system is marginally higher than first scenario that shows the high feasibility of the proposed energy system.

In addition, it should be considered that in the proposed energy system, the WPT system is just added to an available electric city bus without any change in the other energy resources. In fact, the utilization of the WPT easily helps to reduce the size of the battery and FC (both module and tank) which leads to a reduction in their investment costs. For example, based on the Fig. 10, the WPT-based battery charging ratio to the battery discharging in the driving and short stop modes is equal to 0.36. This ratio means that with the presence of WPT system, the size of battery can be reduced by 36-percent without any problem to satisfy all the constraints. In addition to the investment cost reduction, these battery and FC size reduction leads to a lower bus weight which bring a lower load profile and total operation cost. Consequently, the WPT technique alongside with an optimal component sizing would have a higher feasibility.

In the second scenarios, the battery is recharged by the diesel generator (not plug-in) which helps to have a smaller diesel engine and operate the engine with higher efficiency. Based on the results, this scenario has a lower cost (due to the lower energy and investment costs); however, this cost difference can be easily neglected due to its emissions. As a result, the proposed method can be seen as a viable alternative system that can be the future of this industry.

VI. CONCLUSION AND FUTURE WORK

In this paper, the EM related challenges regarding to add a WPT system to the FC-based all-electric bus assessed. It is considered in the proposed energy system that the power can wirelessly transfer from the city power grid to the bus only in bus stations. It has been seen that, due to the intricacy of existing constraints and variety of working modes, the implementation of an EM on such a hybrid energy system is highly complex. So, in order to enhance the search ability of the optimization method, the constraints are mathematically modeled in EM parameters' optimization. The optimal power dispatch results illustrate that the proposed EM method is able to sufficiently satisfy all the constraints. The obtained optimal EM shows a completely acceptable economic results which indicate the applicability of both energy system and EM in industrial and real life applications. All these together illustrate the high feasibility of WPT technique in the subject of all-electric city buses.

As a future work, it is very important to assess a simultaneous EM and component sizing for all-electric city busses with WPT, so that optimal size of an energy storage unit is used. Furthermore, shifting from offline to fast online EM is aimed to analyze how the proposed setup will behave under load and supply uncertainties.

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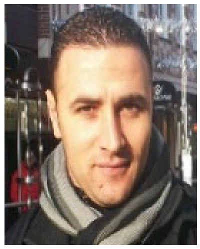

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