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Renewable Integration for Green Urban Mobility: A Case Study of Public Transport Depot Electrification

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Abstract. This paper analyses an electrification strategy for a depot for a public transport company, through an optimized model. The case study analyses both the transition of a depot able to host 10 buses towards e-buses and proposes the integration of a micro-grid, powered by PV panels to power the e-buses in a sustainable way. The study addresses key challenges such as spatial constraints, passenger demand, and financial considerations, through a Genetic Algorithm (GA). The analysis encompasses two scenarios: a mixed fleet of electric and diesel buses and an exclusive focus on e-buses. The study highlights the importance of considering both electric and diesel buses in fleet optimization, and combined with renewables emphasize the advantages of operational flexibility and sustainability. Thanks to the implementation of a micro-grid capable of providing 1123.87 kWh/day to power the e-buses as much as possible.

Keywords. Electric buses, dynamic simulation, local public transport, optimization algorithm, photovoltaic modules, solar energy

1. Introduction

The escalating concerns about environmental degradation, air quality, and the global climate crisis have propelled the need for sustainable solutions across various sectors. One area that has garnered significant attention is the transportation sector, renowned for its substantial contribution to Greenhouse Gas (GHG) emissions and urban air pollution [1,2]. Several authorities have started to promote various decarbonization actions, promoting the use of collective transport. These actions aim to reduce traffic congestions and pollutant agents in urban area. Within this domain, public transportation systems, serving as lifelines for urban mobility, have emerged as critical focal points for transitioning to cleaner and more efficient alternatives. Diesel-powered vehicles, which have long been the backbone of public transportation fleets, are now facing increasing control due to their negative impacts on the environment and human health. The combustion of diesel fuel releases a cocktail of harmful pollutants, including Nitrogen Oxides (NOx) and particulate matter, into the atmosphere [3,4]. In recent years, Electric Vehicles (EVs) have emerged as a promising alternative, offering a cleaner, quieter, and

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more sustainable mode of transportation [5]. By replacing diesel buses with electric counterparts, cities can significantly reduce local emissions of harmful pollutants and GHGs [6]. This transition not only aligns with international climate goals [7] but also contributes to creating more livable urban environments. The key drivers behind the electrification of public transportation are manifold. Primarily, advancements in battery technology have resulted in improved energy storage capabilities, extended driving ranges [8-10]. Moreover, the increasing global focus on clean energy solutions has led to substantial reductions in the cost of EV manufacturing and deployment [11,12]. As a result, the upfront costs of e-buses, once prohibitive, are becoming more competitive, with the potential for long-term operational cost savings due to reduced fuel and maintenance expenses [13]. While the shift from diesel-powered buses to EVs addresses significant environmental concerns, the efficacy of this transition is not solely dependent on the type of vehicles deployed. The presence of EVs within a fleet does not guarantee the achievement of the Net-Zero emissions objective that many authorities are imposing for 2050. To achieve this target, Local Public Transport (LPT) companies are working to integrate their micro-grid depots to integrate Renewable Energy Sources (RES) into the structure. Micro-grids are a simple structure commonly used in the context of power supply of buildings or communities. Moreover, they are modular structures and can be expanded and integrated with new elements with low effort. Therefore, in a rapidly changing urban context, where environmental and social sustainability is crucial. This article aims to provide useful information to policymakers, transport authorities and researchers committed to improving the efficiency and sustainability of public bus service, by RES integration in the depot. To reduce emissions in a well-to-wheel perspective in this work an electrification model of the depot that will host the e-buses is proposed. The simulation for this model is carried out using HOMER software, a widely utilized tool for designing micro-grids and incorporating renewable energy sources [14]. In this context, the depot will be equipped with a 47 kW Photovoltaic (PV) power system, capable of generating 1123.87 kWh/day.

The paper is organized as follows: Section II aims to provide a literature review of the renewable integration in LPT application. In Section III, the methodology used to develop the depot optimal renewal, both for the configuration and for the RES integration. In Section IV, the case study applied to a LPT company is shown. The results are presented and discussed in Section V. Finally, in Section VI the conclusions emphasize the possibility and desirability of this approach for the energetic transition of the sector.

2. Renewable Integration in LPT Application

With the new stringent policies, the decarbonization trend has become a primary problem in several sectors. In particular, the transport sector and the electricity generation sector represent the two main emitters of greenhouse gases. To meet this challenge, several Public Transport Operators (PTOs) have started electrification processes of their fleet and several studies have been proposed in recent years. [15] collects several global case studies on the inclusion of e-buses in fleets [16] highlights how the rider perceives the shift from diesel bus to e-bus. More specifically, [17] proposes an electrification model for a large-scale city bus service in New York. The proposed optimization model uses an algorithm that minimizes the cost of the system and at the same time maximizes the service provided. [18] analyses a European case study, where the impact of a city bus service in Norway is studied. These works underline the importance of decarbonization of the transport sector from the points of citizens, users, and authorities. However, this effort may not be sufficient to achieve the Net-Zero emission target since the massive electrification of the various sectors will lead to an increase in electricity demand [19]. The RESs integration can help meet the growing energy demand of sectors such as transport. Several studies have already started to promote the integration of renewables to electrify e-buses depots. [20] proposes a model of integration of renewables for a cost-efficient energy management system. Similarly, [21] shows the rescheduling of an LPT service through e-buses, satisfying the new electricity demand through the implementation of a solar powered micro-grid. Then, [22] proposes an even more advanced model, in which EVs are used as mobile energy storage. For the development of these renewable integration models, HOMER software is widely used to model optimized microgrids based on the electrical load. [23] provide a techno-economic analysis of energy system using this software in western Saudi Arabia for the electrification of a remote cluster. [24] uses this methodology to perform an economic analysis of PV integration to supply for an EVs in Shenzhen, China. Although numerous RESs integration studies have already been performed, in this work, this aspect will be combined with the optimal sizing of a depot for buses dedicated to LPT.

3. Methodology

In the first part of this study, a depot is conceptualized as a case study for hosting buses in a LPT system. This involves identifying vehicle models, to formulate two optimal scenarios for depot management. These scenarios explore the deployment of either a partially electrified fleet or a fully electrified fleet. To determine the most effective combination of buses meeting criteria such as seating capacity, area constraints, and costs, a Genetic Algorithm (GA) is employed. The GA employs selection, crossover, and mutation processes to iteratively enhance solutions in each generation, ultimately producing the best combination of buses that satisfy the specified criteria for efficient depot management. This approach provides valuable insights into the optimization of depot resources in the context of diverse bus fleets, considering both partially electrified and fully electrified configurations.

Subsequently, a study for the electrification of the depot by integrating a PV plant is proposed. Starting from the case study examined, the quantity of PV panels that can be installed on the roof of the depot will be evaluated. This electricity production will be used to power e-buses through green energy. However, considering that most vehicles will charge during the night, a storage bank will be installed to store the energy produced by the PVs during the day. Moreover, the insertion of batteries will increase the stability of the system. Figure 1 shows the methodology used for the management of the deposit and the integration of the RESs through the implementation of a micro-grid.

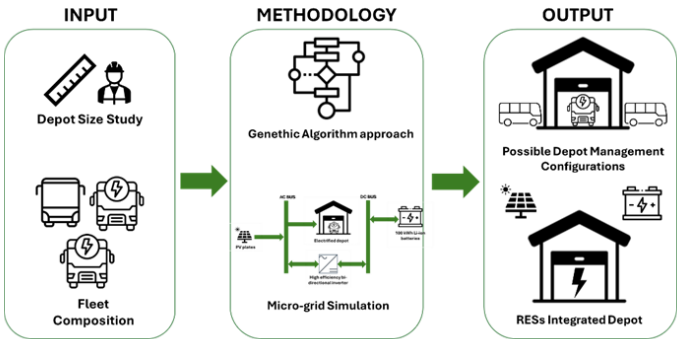


Figure 1. Methodology representation for depot electrification.

For the implementation of the microgrid some preliminary information is necessary. First, it is required the knowledge of the geographical location of the microgrid implementation site. The different position affects the availability of the RESs to be integrated. Subsequently, the size of the electrical load to be powered and its distribution during the day must be known. This parameter has a great influence on the size of the PV plant, since a higher demand during maximum production hours will minimize the quantity of plates and storage systems. PV power production follows (1).

$$P_{out} = \frac{I_g \cdot P_{PV}^n \cdot \eta}{I_{STD}} \tag{1}$$

Where:

- P_{out} represents the PV power produced;
- I_g is the global horizontal irradiance;
- P_{PV}^n is the total rated power;
- η is the efficiency of the component;
- I_{STD} is the irradiance in standard condition.

Since PV plates have limited operation during the day and their production may be affected by uncertainty, the inclusion of a battery storage system is recommended. This will allow night-time loads to be powered and avoid grid instabilities. Finally, a bidirectional converter will be inserted to allow the passage of energy between the DC and AC elements. All the components must respect the bus balance expressed by (2).

$$\sum_{i=1}^{n} P_{abs_i} + \sum_{i=1}^{n} l_i = \sum_{i=1}^{n} P_{gen_i} \tag{2}$$

Where:

- $\sum_{i=1}^{n} P_{abs_i}$ represents the amount absorbed power by the load and the battery, when acts like a user;
- $\sum_{i=1}^{n} l_i$ is sum of all the losses generated by the PVs, the inverters, batteries and cables;
- $\sum_{i=1}^{n} P_{gen_i}$ is the total power generated by the PV plant and the battery if acting like a generator

4. Case Study

The purpose of Section IV is to present a hypothetical case study involving a LPT company depot that seeks to transition to an electric bus fleet, and then supply as much as possible the electric demand through RESs. The depot is faced with the challenge of optimizing its bus fleet composition while considering spatial constraints and daily passenger demand. Through the application of Genetic Algorithm (GA), aim to demonstrate how this optimization process can effectively align with the company's goals of sustainable urban mobility.

The public transportation company operates from a depot with an available parking area of 300 m^2. The goal is to ensure that the bus fleet can accommodate the demand of 900 passengers effectively, while also considering the need for optimal fleet composition that balances seating capacity and spatial constraints. For the case study, some bus models on the market are taken into consideration [25]. Table 1 provides the technical details, such as area, number of seats, battery capacity and price, for each bus model in the fleet.

Table 1. Technical data of the bus fleet composition

Model	Type	Area [m^2]	No. seats	Capacity [kWh]	Price [€]
E-way 9.5m	Elec.	22.135	69	294	300,000
E-way 10.7m	Elec.	24.931	77	294	340,000
E-way 12m	Elec.	30.6	91	335	380,000
E-way 18m	Elec.	45.9	160	623	440,000
Daily access	Diesel	12	35	/	55,272
Crossway Low Entry	Diesel	39.975	110	/	200,000

There are also diesel bus models in the fleet because the transition to an all-electric fleet can take some time due to numerous factors, including costs, charging infrastructure, vehicle availability and other logistical considerations.

The primary objective is to showcase the differences in optimization outcomes when considering a combination of electric and diesel buses versus an exclusive focus on EVs.

Finally, to decrease the impact on the main electricity grid and reduce emissions in a Well-to-Wheel perspective, a microgrid powered by a PV system is simulated using the HOMER software. The micro-grid structure is proposed in Figure 2.

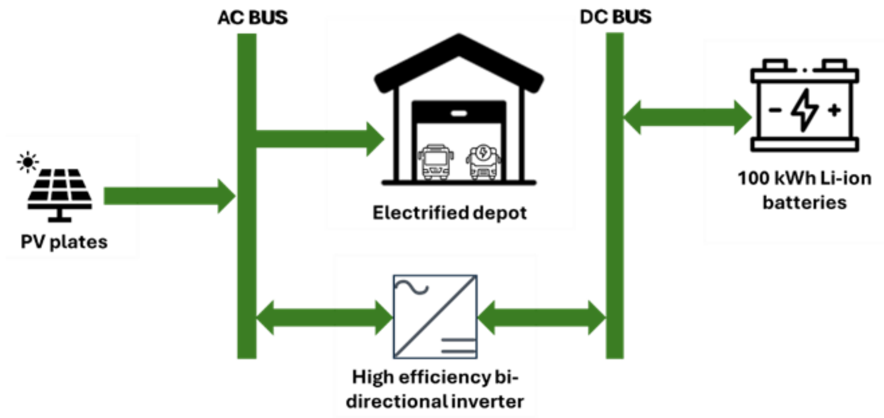


Figure 2. Renewable integration model.

The PV plates used are monocrystalline panels with and produce approximately 1 kW for every 5.5 m^2. The depot was positioned in an area where the global solar irradiance is 3.73 kWh/m^2/day. The identified storage system is composed of Li-ion batteries with a capacity of 100 kWh each (166.7 Ah). It is considered that their charge and discharge cycle go from SoC=95% to SoC=15%, to maximize the useful life of the system. It should be remembered, however, that the size of the PV system will be limited by the space available on the roof of the depot. Finally, considering that most vehicles should recharge during the night, the loading model used is shown in Figure 3.

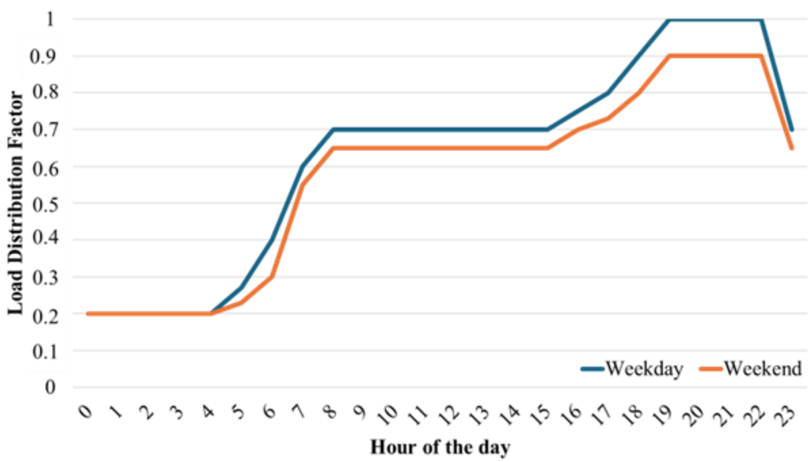


Figure 3. Load distribution model over the day.

Using this load model, it is sufficient to know the maximum load and report it at the various times with the correct load distribution factor to know the average hourly load.

In this study, a dual-scenario approach is employed to comprehensively explore the optimization of a fleet comprising electric and diesel-powered buses. The first scenario encompasses a diverse range of vehicles, considering both electric and diesel buses. Contrastingly, the second scenario focuses exclusively on e-buses, deliberately excluding diesel-powered counterparts. This restriction aims to highlight the environmental benefits and potential cost implications associated with an all-electric fleet. By comparing the outcomes of these two scenarios, valuable insights are gained into the impact of vehicle type composition on fleet optimization. The study underscores the importance of considering diverse fleet compositions in addressing public transportation optimization challenges, providing a comprehensive understanding of the trade-offs and advantages inherent in both approaches.

5. Results and Discussion

The obtained results from the optimization script reveal a comprehensive picture of the fleet composition and its implications under different scenarios. The provided GA strives to achieve the optimal selection of buses while adhering to specific constraints. The following detailed analysis delves into the results, highlighting key observations and insights. Moreover, to reinforce the concept of sustainable mobility, the electrification process of the depot will be integrated with a PV system. With this integration it will be possible to produce energy to partially power the e-buses.

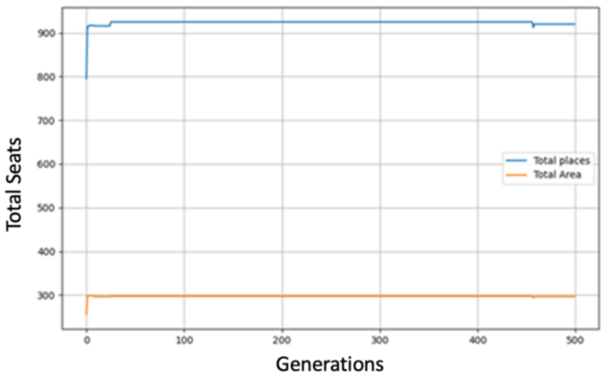
5.1. Depot Management

Through the GA, a fleet of e-buses was identified for the two scenarios, respecting the established criteria. Table 2 shows the model numbers for both scenarios.

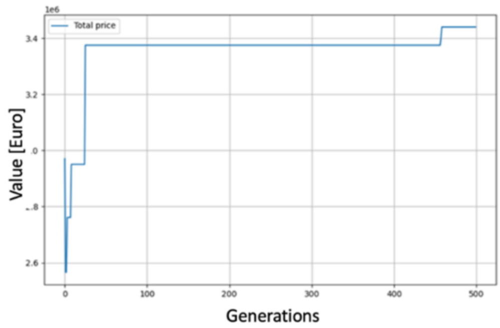
Table 2. No. of bus models according to the scenarios.

		Scenario 1	Scenario 2
Model	**Type**	**No. of buses**	**No. of buses**
E-way 9.5m	Electric	1	4
E-way 10.7m	Electric	4	3
E-way 12m	Electric	3	1
E-way 18m	Electric	1	2
Daily access	Diesel	0	0
Crossway Low Entry	Diesel	1	0

For Scenario 1, the composition totaling 920 seats and occupying 296.534 m^2, signifies the algorithm's success in striking a balance between seating capacity and space constraints, Figure 4a. The total cost, calculated at € 3,440,000, showcases the financial implications of the optimized fleet, Figure 4b.



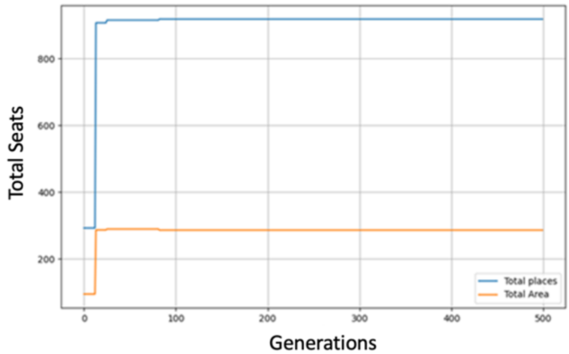
(a)



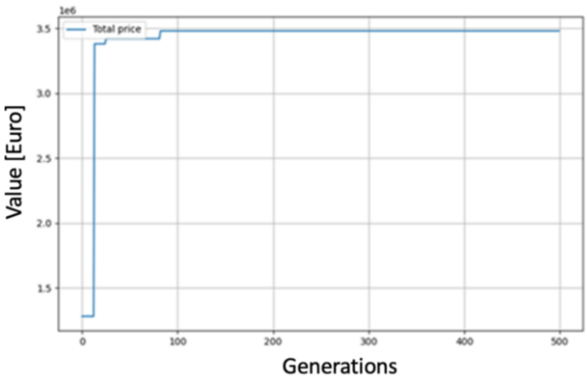
(b)

Figure 4. Evolution of total places, total area (a) and total price (b) over generations (Diesel and Electric scenario).

For Scenario 2, the selected fleet configuration is designed to accommodate a total of 918 seats, fitting within an area of approximately 285.733 m^2, Figure 5a. The fact that this configuration meets both the seating capacity requirement, and the space constraint underscores the algorithm's efficacy in optimizing the fleet. Furthermore, the total cost of €3,480,000 underscores the financial implications of the selected vehicles and their potential impact on operational budgets, Figure 5b.



(a)



(b)

Figure 5. Evolution of total places, total area (a) and total price (b) over generations (Electric scenario).

5.2. Depot Electrification and Renewable Integration

Considering the available area of 300 m^2 and the size of the installable PV panels (5.5 m^2/kW) and the unavailable spaces, the maximum installable power is approximately 50 kW. The daily variability of the load is reduced to 5%, as the PV plant is not sized exactly on the load to be supplied but rather on the space available on the roof of the depot. Through a simulation performed with the HOMER pro software, Table 3 shows the main electrical outputs.

Table 3. PV plates electrical output

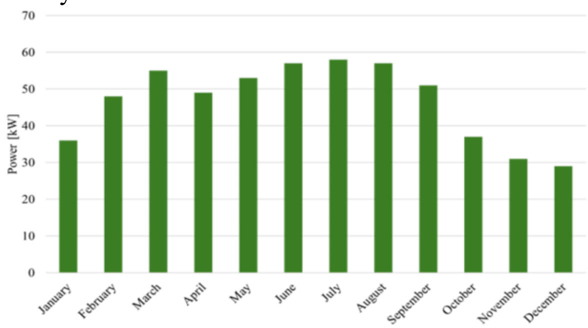
Quantity	Value [unit]
Rated Capacity	316 [kW]
Mean Output	47 [kW]
Mean Energy Output	1123.87 [kWh/day]
Yearly Energy Production	410214 [kWh/year]
Maximum Output	325.68 [kW]
Hours of operation	4375 [h/year]
Levelized Cost of Energy Production	0.147 [$/kWh]

In addition, to supply the e-buses during the night and avoid grid instabilities, a storage bank is inserted. The storage system is composed by Li-ion batteries with a capacity of 100 kWh each and a DoD (Depth of Discharge) of 80%. Table 4 collect the information which highlight the operation of the storage bank to assist the PV plant.

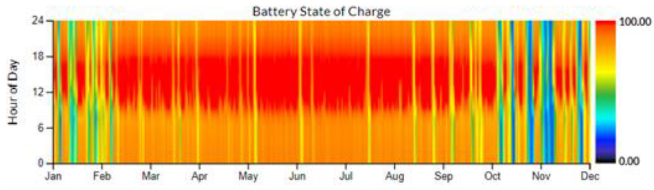
Table 4. Storage bank electrical output

Quantity	Value [unit]
Strings in Parallel	15
Bus Voltage	600 [V]
Usable Nominal Capacity	1200 [kWh]
Autonomy	58 [h]
Battery wear cost	0.049 [$/kWh]
Annual throughput	99991 [kWh/year]

In this context, Fig. 10 shows the monthly rate of use of the PV plant and batteries. For PV plates it can be shown thanks to the monthly profile of the average production of PV plates (Figure 6a). On the other hand, for the storage system it is possible to use the heatmap shown in Fig. 6b, which shows the SoC of the stationary batteries during the months of the year.



(a)



(b)

Figure 6. a) PV power production during the year, b) storage system rate of use.

Thanks to this comparison the micro-grid is sized in an optimized way and the number of batteries is sized so that the SoC does not fall below values of 15%, to avoid excessive wear. In periods of minimum PV production, between October and January, the batteries will be more stressed, having to act as a power supply, for longer due to the lack of solar irradiance. This will ensure that the batteries reach values close to the acceptable minimum. Finally, it should be considered that the depot strategy involves using all buses once a day with a DoD=80%. Therefore, considering this bus management strategy, the energy demand for the buses in the first scenario will be 2478.4 kWh/day. On the other hand, in the second scenario, the energy demand will reach 2911.2 kWh/day. Through this model it will have been possible to power 45.34% with green energy in the first scenario, while in the second scenario, 38.60% of the demand will be powered by the new integrated microgrid.

6. Conclusion

Following the introduction of new stringent policies to combat climate change, the public transport sector began to change radically. LPT companies started a process of fleet decarbonisation, replacing ICE buses with e-buses. This transition has changed the management of the depots and their energy needs, since the buses will be powered by electricity. However, the decarbonization of the service offered by the PTO is not completely decarbonized. The lack of an environmentally sustainable energy supply would cause emissions to be shifted from the user to the generator. To address these challenges, this work proposes a management model for a bus depot that is making the transition to electric optimized through a GA. Furthermore, the depot will be integrated with a microgrid powered by photovoltaic panels flanked by a storage bank, to power the buses that will recharge in the depot with sustainable energy. The model will first suggest the choice of buses to facilitate the transition, after which, with a micro-grid that will have an average daily production of 1123.87 kWh, the buses will be powered in a sustainable way for the 45.34% and the 38.60% of the demand. The progress of the electrification of these sectors will facilitate the entry of new technologies to support the resilience of the electricity grid. The integration of V2G (Vehicle to Grid) or further stationary storage systems will favour the development of a smart and resilient network, allowing new case studies of interest for the future. The case studies will be both resilience and RES integration oriented. Through this work, it is proposed a decarbonisation strategy for the transport sector and by integrating the depot with a RES, the aim is to reach the Net-Zero emission target set for 2050.

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