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Systematic Review

Public Transport Decarbonization: An Exploratory Approach to Bus Electrification

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Abstract: In 2020, only 0.9% of buses running in European Union countries were electric, with 93.5% still being diesel-powered. The Sustainable and Smart Mobility Strategy set out by the European Commission targets a reduction of at least 55% in greenhouse gas emissions by 2023 and the achievement of climate neutrality by 2050. These targets will only be met by a shift to sustainable mobility, which comprises the introduction of electric vehicles in cities and the adoption of battery electric vehicles (BEV) for urban public transport. Thus, a literature review on "electrification of bus fleets" was conducted, focusing on the practices adopted for the replacement of polluting buses with electric-powered ones. A total of 62 documents were included in the final investigation, and their results were used to conduct a SWOT analysis. It is possible to conclude that BEBs are an important asset for cities to decarbonize the transport sector and that they are more cost-effective than diesel buses. On the other hand, some attention needs to be given to the generation of energy that will feed the charging of batteries because the use of fossil fuel energy sources can jeopardize the environmental benefits of BEBs.

Keywords: public transport decarbonization; BEBs; BEB systematic review

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1. Introduction

In 2020, there were more than 684,000 buses in use in the European Union. However, 93.5% of them were diesel-powered, with only 0.9% relying on electric batteries [1]. The Sustainable and Smart Mobility Strategy set out by the European Commission targets a reduction of at least 55% in greenhouse gas emissions by 2023 and the achievement of climate neutrality by 2050, which will be reached by introducing more ambitious policies to reduce the transport sector's reliance on fossil fuels [2]. Therefore, the electrification of road transport, combined with a modal shift towards public transport, is crucial to achieving the decarbonization of the transport sector [3,4].

The transport sector is ranked among the economic sectors responsible for most of the greenhouse gas emissions in the European Union [5]. It registered an increase of 7% in greenhouse gas emissions from 2021 to 2022 alone, making it the economic sector with the highest increase in this period [6]. Road transport still accounts for the highest proportion of overall transport emissions, emitting 76% of all European Union's transport greenhouse gas emissions; thus, most of the state members' focus on decarbonization is related to this matter [7].

The electrification of bus fleets in cities could bring benefits for transit agencies as well as the surrounding communities because electric buses are more energy efficient than diesel buses and have fewer moving parts, thus potentially decreasing fuel and maintenance costs. They also have a quieter operation and zero harmful tailpipe emissions [8]. However, large-scale deployment of e-buses requires significant incremental power capacity and a corresponding increase in renewable generation capacity [9].

Although the demand for energy consumption will increase when battery electric buses (BEBs) are implemented, adding to the high financial costs associated with the purchase of vehicles and the infrastructure needed for charging stations, BEBs can lead to an expansion in public transport usage [10]. The adoption of BEBs in urban areas increases people's willingness to pay to use public transport. Examples from China and Spain show that BEBs increase people's willingness to use public transport as well as paying more to use the service [11,12].

The deployment of BEBs in cities could also improve the quality of travel for people with different trip purposes due to their performance [13]. A study performed in Utah, USA, showed that commuters would prefer to make their journey in an electric bus due to the quieter engine that allows them to read or work, while people who travel for leisure activities value BEBs for their smooth and comfortable ride [14]. The preference for greener modes of transport was also reported by Sunitiyoso et al. [15], whose investigation pointed out that commuters prefer buses and trains over other modes and that electric buses are preferable to conventional buses.

Taking into consideration the need for greener road transport modes and the acceptance of electric buses by the target population, it is of utmost importance that polluting buses are replaced with new electric-powered ones [16]. Therefore, Pelletier et al. [17] proposed an electric bus fleet replacement method by taking into consideration crucial factors such as purchasing costs, salvage revenues, operating costs, charging infrastructure investments, and demand charges. In Portugal, a methodology for the replacement and scrapping of polluting buses takes into consideration the need to replace running buses that are up to 14 years old, meaning that by 2034, all buses in the country would be replaced with green ones [18].

The shift from combustion-powered engines to battery electric vehicles is a key factor in the decarbonization of the transport sector. The replacement of less than half of the fuel-powered vehicular fleet with battery electric ones in Greece could represent a 13% reduction in CO_2 emissions by 2023, a 57% reduction in NO_x emissions, and an increase in people's quality of life [19]. Thus, the average age of buses in Europe and around the globe will decrease with the introduction of new and green vehicles. At around 20 years old, Romania has the oldest bus fleet in Europe, followed by Greece (19 years) and Poland (16 years) [20].

Around the world, the average age of buses is 6.9 years, but the average is affected because of the younger buses used in China, Russia, and Brazil [21]. Even though the average age of buses is low, almost 70% of them run on diesel or diesel plus additives, with 28.3% of the fleet meeting Euro V standards and 22.5% meeting Euro III standards [21].

Thus, this research aims to explore, characterize, and understand how the decarbonization of urban bus fleets is achieved around the world in order to propose a framework for best practices in the replacement of polluting buses with electric-powered ones. The systematic analysis takes into consideration the evaluation of relevant aspects of bus replacement, such as the role of green energy in powering BEBs, the costs of vehicle replacement and the infrastructure needed (i.e., charging stations), and possible changes to travel demand when BEBs are incorporated into public transport options.

The remainder of this paper is structured as follows: Section 2 presents the methodology used in the research work. Section 3 presents the results and analysis of the data collected, providing an overview of the main topics related to the introduction of electric buses into urban bus fleets, such as the differences in GHG emissions, the life cycle of the replacement for this new type of bus, and alternatives to implementing BEBs in public transport. Section 4 covers the discussions and conclusions of the research work.

2. Methodology

In order to ensure a comprehensive approach to the practices adopted for the replacement of fuel-powered buses with battery electric ones in urban mobility, the following four-step systematic process was followed [22]: (i) identification of documents through the search of online databases; (ii) screening process and incorporation of additional literature; (iii) qualification assessment; and (iv) incorporation in the final analysis [23,24].

Two databases were considered for the gathering of relevant studies: Scopus and Web of Science (WoS).

The first step of the process concerned the gathering of documents written in English and published within the time period between 2014 and 2023. The research in the databases was conducted for the presence of the following terms in the title, abstract, or keywords of the documents: “bus electrification”, “battery electric bus”, “bus decarbonization”, “electric bus”, “public transport decarbonization”, “bus electrification pathway”, and “alternative fuel bus”. The research was carried out in October and November 2023. Table 1 presents the number of records that were gathered in the two databases.

Table 1. Terms used for research in Scopus and Web of Science (WoS).

Terms	Scopus	WoS
(“electric”) AND (“bus”)	522	55
(“bus”) AND (“electrification”)	84	3
(“bus”) AND (“decarbonization”)	14	3
(“battery”) AND (“electric”) AND (“bus”)	318	12
(“public”) AND (“transport”) AND (“decarbonization”)	9	5
(“bus”) AND (“electrification”) AND (“pathway”)	3	0
Total	1028	

After the first stage of screening, excluding duplicate documents, and evaluation of the suitability and adjustment of each research work to the topic, 62 articles remained eligible for the systematic review on bus electrification. The remaining papers were selected because they presented some of the following attributes:

- Focused on the assessment of the decarbonization of passenger transport in urban environments, along with case studies that take into consideration the environmental aspects of the replacement of fuel-powered buses with less polluting fuel options, including electric batteries;
- Included a sensitivity analysis of costs, the difference in energy consumption with the introduction of BEBs, the location of the charging stations, and possible scheduling of the routes for BEBs;
- Analyzed the willingness of consumers to pay for BEB services in comparison with traditional bus services that are fuel-powered.

The next step consisted of using the snowball technique [25] to incorporate additional documents that concern policy reports and white papers on the decarbonization of road transport, which culminated in a total of 84 documents to be used in this systematic review. In this step, additional gray literature was retrieved by tracking down the reference section of the literature already selected to compose this literature review. This additional literature brings to light current efforts that are being made by governments and regulatory agencies to promote the decarbonization of the transport sector, including public transport options in an urban context. Figure 1 presents the flowchart for the evaluation of relevant documents to be added to the systematic review.

The final analysis comprised the incorporation of all documents retrieved from the databases and was used to weigh the different perspectives on the incorporation of electric buses in urban transport so that a SWOT analysis can be conducted to evaluate the strengths, opportunities, weaknesses, and threats of the decarbonization of the public transport sector and a better strategic plan can be achieved when planning the sustainable transition of mobility in cities.

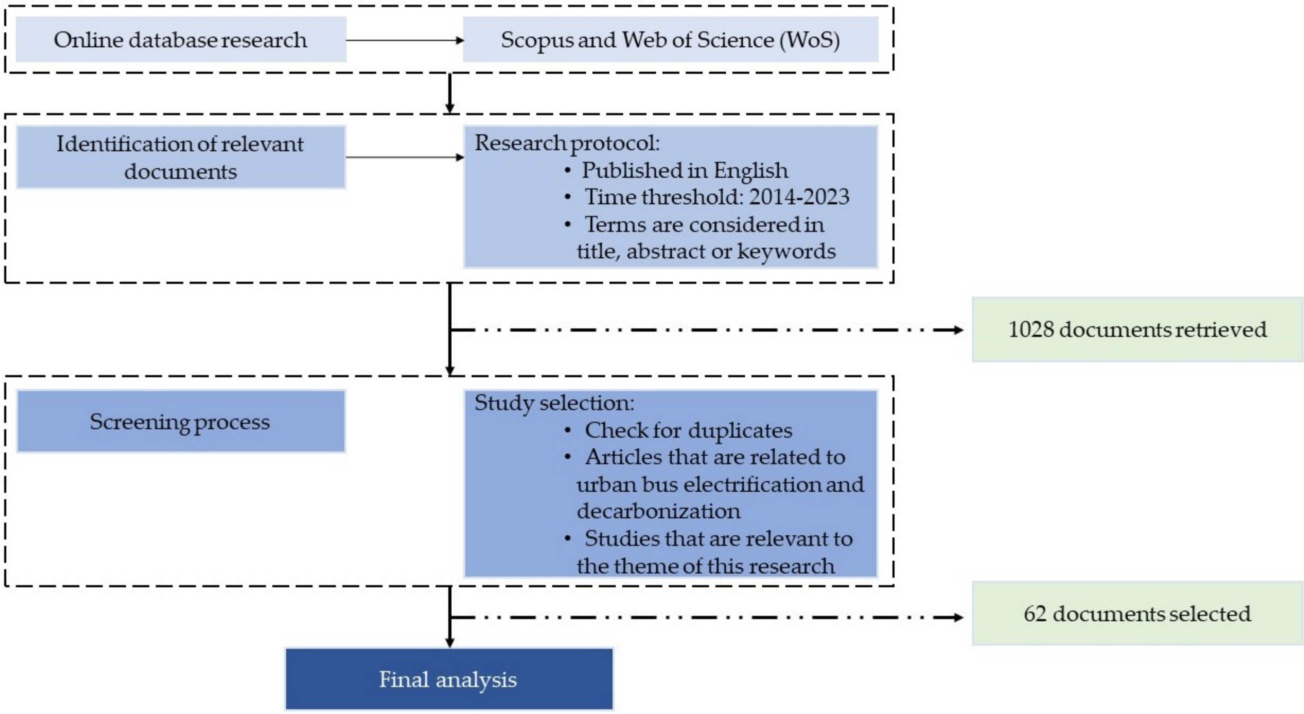

Figure 1. Methodological flowchart.

3. Results and Analysis of the Selected Documents

3.1. The Role of Electric Buses to Decarbonize the Transport Sector

The sales of zero-emission buses have been increasing in the European Union. In the last five years, the sales of this kind of vehicle have increased from 400 in 2016 to 2500 in 2021 [26]. By the end of 2021, the bus fleet of nearly 700,000 in the European Union comprised over 9000 electric and 20,000 natural gas buses [26]. The EU also requires national governments to encourage the achievement of the objectives targeted at the provision of sustainable modes of transport as well as the manufacturing of vehicles that release less pollutants.

One of the biggest problems faced when replacing diesel-powered buses with BEBs is the cost of the vehicles. The purchase of BEBs seems to not yet be cost-competitive with diesel-powered buses, although the purchase prices are falling, primarily due to falling battery prices, and this should make electric buses cost-competitive within the next few years [27]. Under some conditions, the use of hydrogen (initially in internal combustion engines and later predominantly in fuel cells) would be more cost-efficient than electric batteries in buses, but the presence of specific policies is relevant for the use of BEBs in urban public transport [28]. Moreover, the European Union is keen to develop strategies and directives for the electrification of public transport in cities, with a special focus on demonstrating how cost and energy can be saved by electrifying public transport and optimizing the use of existing infrastructure to develop new concepts and business cases [29,30].

The policies that have been implemented in the EU to reduce pollution originated in the transport sector and rely on two main standards: (i) carbon emission standards for fuels and (ii) the implementation of electric vehicles in the urban fleet. A study compared the outcomes of these two policies regarding the achievement of the targets for GHG emissions in the EU. The results show that the development of new technologies would aid the electric vehicle industry, mainly in the production of new and more efficient batteries, although carbon emission standards could be a better solution in terms of cost-efficiency as they contain an incentive to improve fuel efficiency. With endogenous technological progress, the cost of saving CO_2 emissions is reduced from some 200 EUR/ton of CO_2 in a static model to about 100 EUR/ton CO_2 [31].

Taking a specific look at the bus electrification scenario, Lu et al. [32] state that the life cycle evaluation of electric, hybrid, and diesel buses shows that the replacement of conventional buses with hybrid and electric ones can provide a good balance between financial and environmental needs. The same study shows that electric buses outperform hybrid buses in terms of GHG emissions in most European countries; the performance varies with the month of the year and the country. For example, the use of electric buses could reduce overall GHG emissions during summer compared to winter in Estonia and Poland, while in Malta and Cyprus, it would be the opposite due to weather conditions that make electric buses spend more energy during colder winters.

In another case study in Brazil, the electrification of the passenger transport sector is estimated to accomplish the most reduction in emissions if carbon pricing is increased and more efficient engines are used in buses, which means the electrification of the fleet [33]. On the other hand, even if the utilization of hydrogen fuel cell buses would reduce pollutant emissions, their cost (i.e., fuel economy, bus cost, and maintenance) would be 133% more expensive than conventional diesel-powered buses [34]. The purchase of electric buses, in this context, could either work on a full-lease model (i.e., a consortium formed between an energy utility and an electric bus manufacturer) or in a partial-lease model (i.e., energy utility solo performance), which would simplify the purchase and deployment of BEBs [35].

In Reykjavik, Iceland, where the electricity grid is fully decarbonized, the electrification of the passenger transport vehicle fleet is not sufficient to reduce the total indirect emissions; therefore, some more radical actions need to be taken, such as the use of MaaS options, behavioral change, densification of the urban fabric, and implementation of improved public transport [36]. Moreover, the provision of reliable public transport with proper infrastructure can lead to a modal shift, and, together with clean energy grids and BEBs, the targets for the reduction in GHG emissions can be achieved [37].

Results from a study performed in Greece [38] also corroborate the understanding that to reach European standards for GHG emissions, more action than the electrification of the bus fleet is needed, such as the application of techniques that contribute to efficient traffic management and the implementation of measures that upgrade public transport services. Another issue that needs to be addressed when replacing diesel-powered buses with less polluting and green ones is the infrastructure needed for fueling the new buses, which includes the infrastructure needed for CNG fueling stations, gas upgrade companies, and even charging stations for BEBs [39].

Despite the 1.10% annual growth in transport demand in British Columbia, Canada, when there is a shift to electric vehicles for urban journeys and when public transport is electrified, emissions in the long term can be decreased by 95% [40]. The benefits from the electrification of the bus fleet can be different depending on the contexts in which they are inserted, although the benefits of electrification are positive everywhere and can reach quite a large scale when compared to diesel buses [41].

Moreover, the energy that comes to the charging stations for BEBs needs to also be studied and analyzed because the power grid can affect the life cycle emissions of electric batteries. The environmental impact over the life cycle of a BEB is no doubt further reduced when compared to traditional buses; however, charging opportunities can be better specified to improve environmental gains [42,43]. As an example, the possibility of having a solar-powered charging station for BEBs could reduce operational costs by 8% during day-to-day operations [44]. Figure 2 illustrates how charging can be managed to improve the environmental sustainability of BEBs.

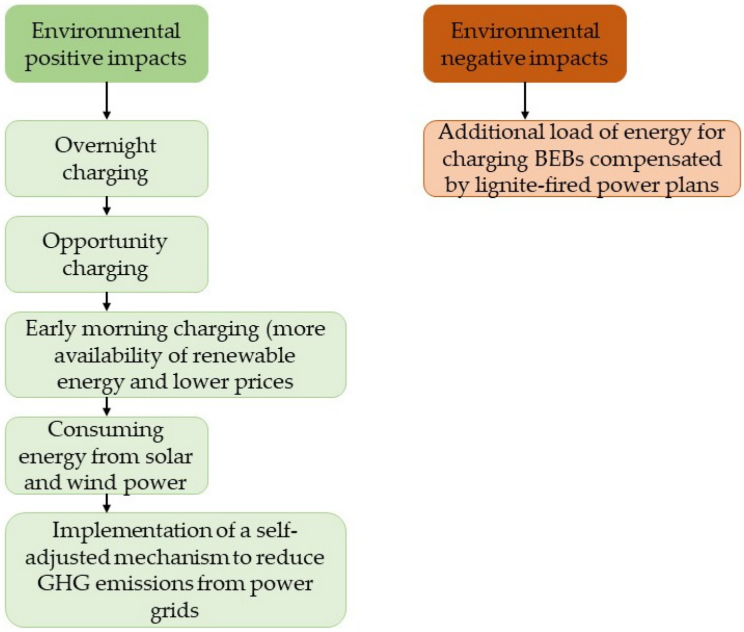

Figure 2. Influence of charging stations on GHG emissions from the life cycle of BEBs. Source: [42,45].

In addition to recharging the batteries and the power plans used to do so, the life cycle of the batteries needs to be investigated as well. Buses that are powered with heavier batteries seem to have higher battery-related emissions, and studies have shown that a battery capacity of 120 kWh has a better life cycle impact than a 60 or 300 kWh battery [46]. The adoption of traffic operations benefits the retrofit of energy and, in certain congestion scenarios, also affects the environmental performance of public transport, with positive impacts [47].

Despite the possibility of GHG emissions in some circumstances of electrification of the bus fleet in cities due to battery-related life cycle and energy production discharges, the replacement of diesel-powered buses with BEBs can represent a lowering in pollution when considering the trip itself [48,49]. A study performed in Portugal [16] showed that in a 14-year timeframe, it is possible to fully decarbonize the bus fleet of the country and consequently reduce GHG emissions to zero. This change would represent a reduction of more than 4 million tons of CO_2 emitted into the atmosphere from one country alone and only from urban buses [16].

3.2. The Assessment of the Life Cycle of BEBs

In order to assess the life cycle of BEBs and how they affect the environmental burden of this mode of transport, it is important to consider either well-to-wheel or tank-to-wheel emissions [50]. The transition to BEBs is the most promising solution for an environmentally friendly urban bus fleet [51]; however, for cities to take full advantage of the decarbonization of the fleet, power grids need to comply with green energy levels and standards.

If electricity production becomes free of fossil fuels, electrified vehicles, as well as BEBs with external charging capabilities, could reach their full potential in mitigating global warming [52]. Also, the costs associated with recharging the vehicles can be lower than the prices of refilling diesel-powered public transport vehicles, which increases the costs for the overall management of buses.

A study by Jakub et al. [53] showed that the shift of electricity production to renewable and low-emission sources would significantly reduce well-to-wheel emissions, which is the main environmental burden of electric buses. In addition, it has been shown that the production of the bus itself has an insignificant burden when compared to the well-to-wheel phase when power grips are not decarbonized. And, as is expected, compared to diesel buses, the tank-to-wheel phase does not represent a significant environmental load.

Even if BEBs are much more expensive than other types of urban buses, their energy efficiency, zero-emission operation, reduced dependence on fossil fuels, and expected cost reductions make them a relevant choice for the replacement of diesel buses [54,55]. The deployment of BEBs in cities is better than conventional diesel buses over their life cycle regarding most of the indicators, such as carbon footprint and reduction in air pollution [56,57]. In some cases, like Vietnam, Sweden, and Norway, if BEB operations could have a supply of renewable energy, the carbon footprint could be reduced to 38.1 g CO_{2eq}/pkm [56,58,59].

Added to the fact that there is a reduction in emissions per passenger kilometer traveled, electric buses have an effective life cycle cost (EUR/KM) when compared to other types of buses. An assessment carried out by Lajunen and Lipman [54] stated that electric buses are more competitive than CNG and diesel hybrids when fossil fuel costs are higher and that BEBs with opportunity charging are more cost-effective than those that are charged overnight.

Thus, the life cycle costs and environmental externalities of BEBs can be affected in the future by some favorable trends. Tong et al. [60] exemplify that technological advancement in the future can corroborate the decrease in battery purchase costs as performance improves. In addition, energy policies from governments can create and improve on even more clean power plans, and BEBs are easier to integrate with intelligent control technologies. These opportunities can make the external costs of electric buses lower than the life-cycle external costs of conventional diesel buses by 2030 [60]. Figure 3 presents a diagram that represents the assessment of the life cycle of BEBs.

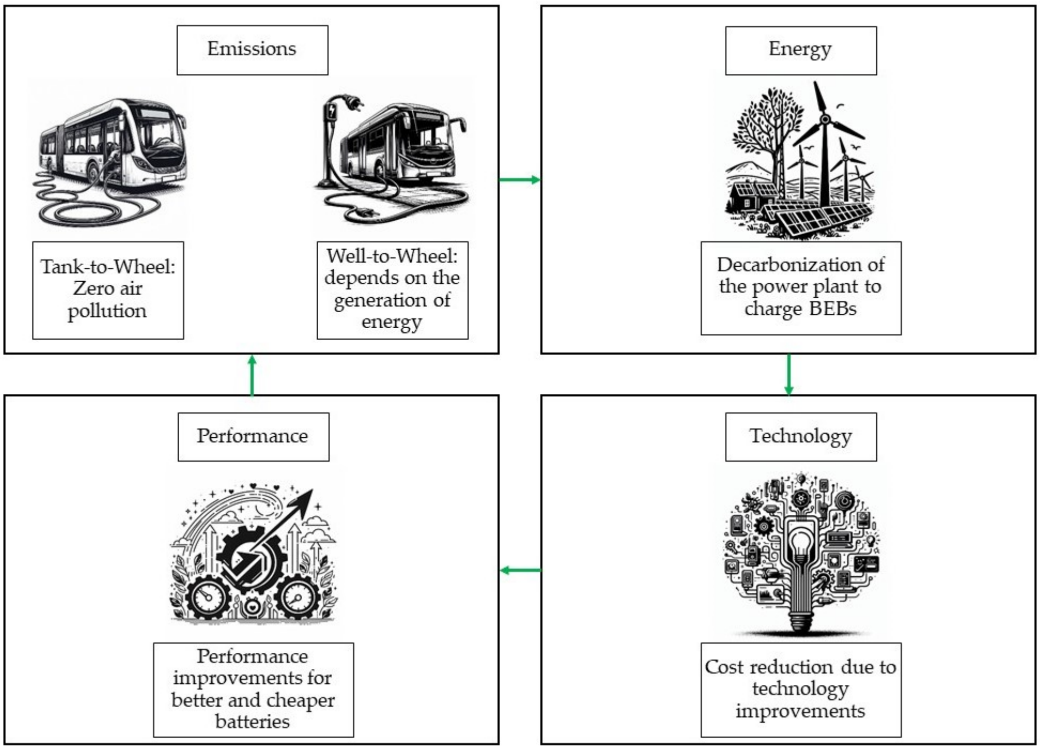

Figure 3. Assessment of the life cycle of BEBs.

3.3. Electric Buses as an Efficient Public Transport Option

One of the main challenges of incorporating electric buses into the public transport fleet is to identify the most suitable solutions for each context, which comprises the most convenient tools that neither dramatically change the daily operation of the buses nor exceed the personnel, investment, and operational boundaries [30]. Thus, it is of utmost importance to better evaluate some aspects of the electrification of the bus fleet, such as the fleet size, charging models, the intended profitability, and the feasibility of the fleet.

The availability of BEBs in the market has been growing in the last few years, which can support the addition of this type of bus to public transport lines. BEBs are seen to have a high potential for urban public transport services because they can represent economic savings of up to 6.0% when compared to traditional buses. Even if the initial costs are higher than current diesel-fueled buses, BEBs are cheaper to operate, and they do not require a completely new infrastructure system but offer synergy with the existing electricity system [61–63]. They can also serve as a way to decrease the external costs of transport, which increases the convenience of having BEBs in the urban fleet [64].

A study performed in Canada shows that the addition of BEBs to the fleet and routes is capable of fulfilling the operational demands required in cities and that electric buses coupled with fast-charging technology would outperform regular BEBs [65]. However, fast-charging buses would need more electrical infrastructure and would not be a feasible solution in cities. On the other hand, regular charging stations for BEBs can be allocated on-route in highly dense service locations (e.g., downtown or central business districts) where several routes are operating to cover relatively smaller geographical areas, meaning the buses pass a main transit hub multiple times a day [66].

Studies show that the most efficient charging scheme is to install charging stations at the end stops of buses instead of along the route, although it is important to mention that a small portion of charging stations (10% to 25%) needs to be installed at stops along the route, depending on the optimization preference for the bus line [67–70]. Electric buses usually take 10 min to be charged, depending on the size of the battery and the power tension available, but are often charged overnight from 8 p.m. to 3 a.m. to secure capacity and availability of energy [71]. Also, the implementation of shared charging hubs for electric vehicles and electric buses can enable coordinated charging that reduces peak power demands and leads to savings in both initial capital investments and long-term peak demand charges [72].

The time of the day when BEBs are charged can also impact the overall cost of operation for this type of bus. In cities that have cheaper nighttime electricity prices, the BEB fleet can be charged at this time to benefit from reductions in refueling costs, as recharging during peak hours can lead to higher costs [42,73]. Moreover, the minimum battery capacity of each bus line must be identified so that the entire route can be completed during the day without the need for refueling, and the buses can be charged at nighttime at the end stop [74]. Figure 4 shows a schematic representation of the characteristics of the introduction of BEBs as a public transport option in cities.

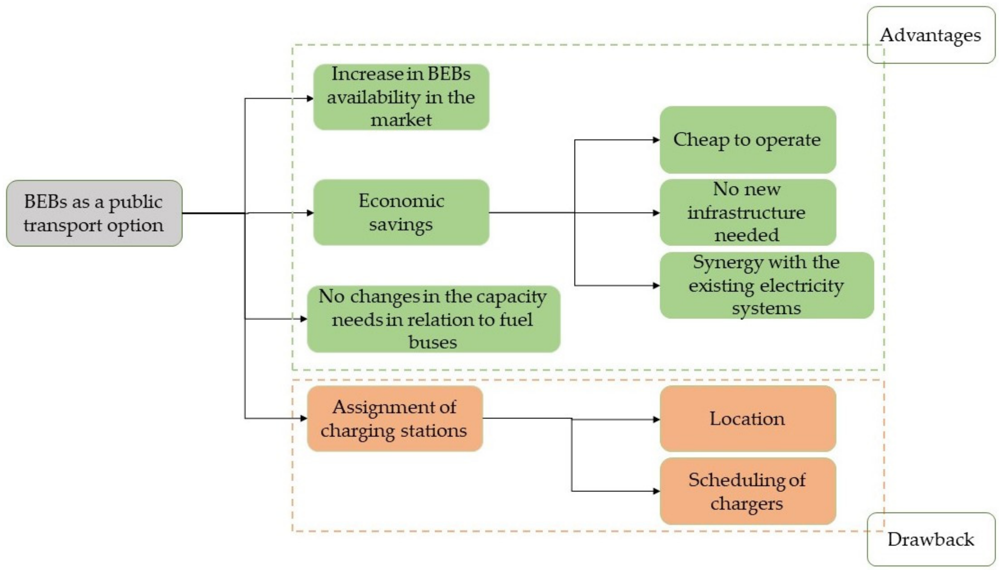

Figure 4. Characteristics of the introduction of BEBs as a public transport option.

In short, the success of the deployment of BEBs in cities when considering the cost-effectiveness of charging infrastructure and route assignment depends on the following main factors that need to be considered by the operator: (i) appointing routes according to the capacity of the batteries; (ii) placing charging stations at endpoints of the routes (end stops); (iii) charging BEBs at nighttime due to lower energy costs and availability of energy; and (iv) initial deployment of BEBs in more dense areas where they can cover more routes in a smaller area. The deployment of BEBs in cities in a way that regular charging can be controlled by the route chosen is the best way to reduce costs and increase the usability of this type of bus in cities [75–78].

4. Discussion and Conclusions

The decarbonization of the transport sector is urgent in order to meet the goal of reducing GHG emissions in the next few years. With vehicles likely to be replaced just two to three times between now and 2050, meeting climate goals requires urgent action, and that includes the introduction of BEBs in urban public transport [79]. Since the Paris Agreement in 2015 up to 2021, the number of nationally determined contributions (NDCs) set by signatory countries that contain concrete targets for reducing the transport sector's carbon emissions has increased from 8% to 16% [80]. This is a beacon of hope that vehicular use will become decarbonized, both by a modal shift from cars to active modes and by the introduction of decarbonized public transport [81].

Moreover, an integrated approach to electric mobility and public transport would lead to the most significant reductions in annual and cumulative direct and indirect GHG emissions [82]. This is seen as an opportunity for policymakers to support the deployment of electric buses in cities.

However, there are some challenges to incorporating BEBs into the urban fleet. These come from the high initial costs to purchase the vehicles and the implementation of charging infrastructure. In addition, the increased consumption of grid energy to meet demand can lead to increased GHG emissions until the decarbonization of the power system is achieved to promote a fully decarbonized fleet [83]. On the other hand, despite the high costs during the implementation process, electric buses are more cost-effective than diesel buses in the long run, and people are willing to use and pay more for this addition to mass transport [12,84].

Regarding all the new uncertainty around the implementation of BEBs in urban areas, this systematic review brought to light key aspects of the operation and life cycle of electric buses in cities. A SWOT analysis was conducted to better understand the main strengths (S), weaknesses (W), opportunities (O), and threats (T) of the replacement of the bus fleet with electric vehicles (Figure 5).

The SWOT analysis corroborates the consideration of BEBs as a way to help the decarbonization of the transport sector and consequently reduce GHG emissions into the atmosphere. The environmental benefits of BEBs compensate for the initial costs for the purchase of this type of bus, and in the long run, they experience a reduction in operational costs when compared to diesel buses. This is due to the lower cost of electricity for recharging the batteries, energy efficiency, and reduced maintenance costs.

On the other hand, with the introduction of electric buses to urban fleets, it is expected that an increase in energy consumption will occur, although this problem can be overcome if the operator schedules the fueling for nighttime hours when the price is reduced and there is more availability of energy [85,86]. The current time frame for the replacement of batteries is increasing through the development of new technologies that enable an expansion of the lifetime of such parts of the vehicle, which will reduce the costs for the operation of BEBs.

The need for charging the batteries can lead to the need for extra grid energy to allow both dwellers to use energy for their homes and their daily activities as well as for the charging of bus batteries. This becomes a problem if extra power needs to be generated from polluting power plant sources, such as coal. In some contexts, such as Portugal, which has achieved the goal of running entirely on renewable energy sources for six days [87], the extra grid energy needed can be compensated. However, in some other regions, this may not be feasible. Thus, the context of energy production must be evaluated where BEBs are implemented; otherwise, the environmental gains of running the bus can be jeopardized by the losses incurred from increased energy production.

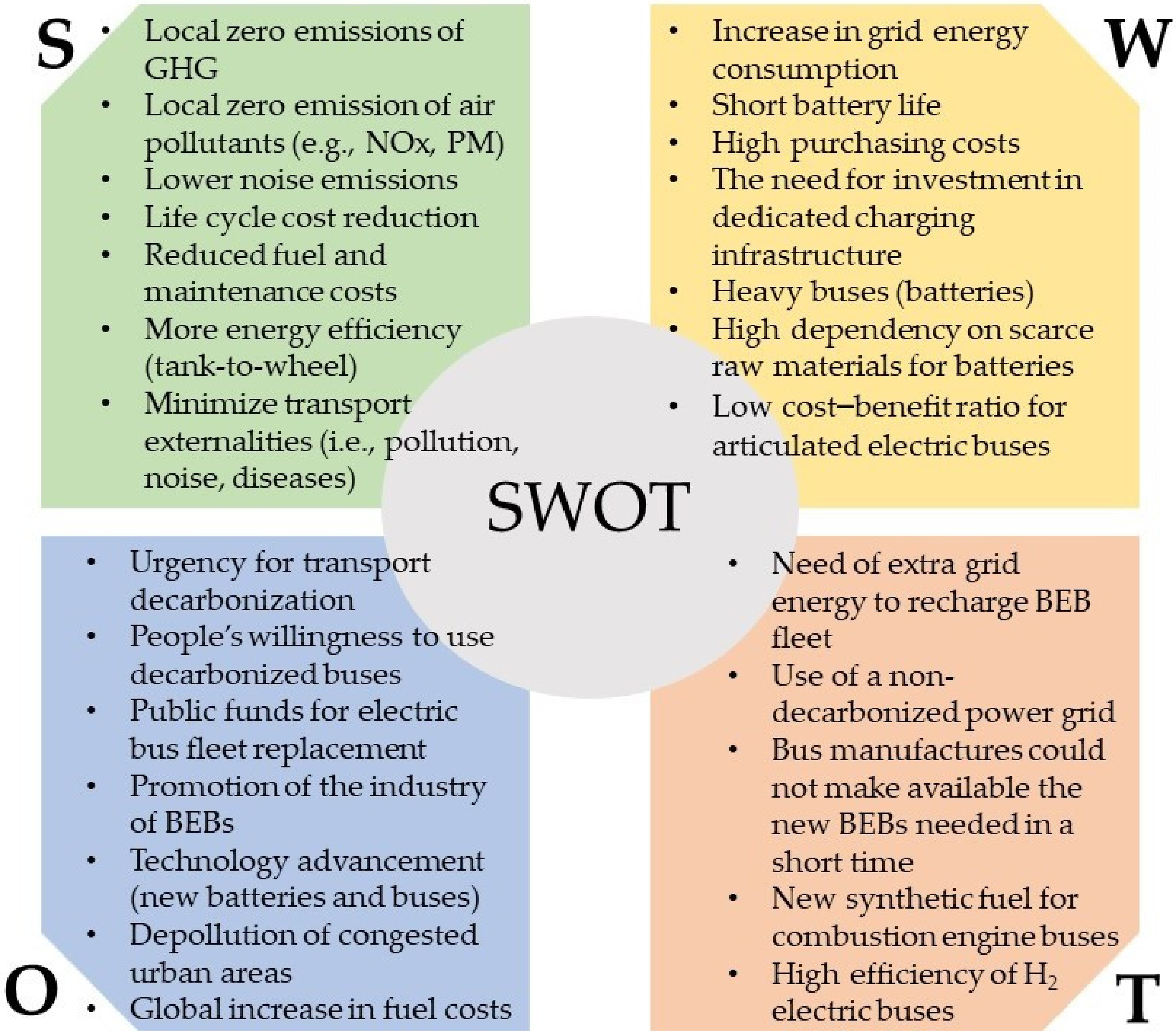

Figure 5. SWOT analysis of bus fleet decarbonization.

Despite the threats and weaknesses of the electrification of urban buses, the number of opportunities for the future is high. Undoubtedly, the deployment of BEBs is a gain for the transport sector in terms of decarbonization, and the current needs and available funds for public transport decarbonization can boost the use of non-polluting vehicles. This adds to the proven fact that BEBs can promote a modal shift in cities because people are willing to use this mode of transport and are also inclined to pay more for this service [12]. This opportunity alone can be used to solve two different problems in cities: congestion, as car users would shift to public transport, and pollution itself. Soon, it is expected that BEBs will infiltrate more and more cities due to increased investment, and the advancement of technology can contribute to the growth of BEB production as well as improvements in the lifetime of batteries.

In short, BEBs have a great potential to help decarbonize the transport sector and promote a modal shift from cars to public transport. Even if the initial costs can be high, there are currently opportunities for funding in order to help with the acquisition of these vehicles and to implement the charging infrastructure needed for them. On the other hand, careful attention must be paid to energy production where BEBs are implemented to ensure increased clean energy production. Therefore, efforts need to be made to provide a clean and green life cycle for the deployment of BEBs as well as for their operation so that the decarbonization of urban bus transport is environmentally friendly from all aspects.

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