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Electric buses: A review of alternative powertrains

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ABSTRACT

Evidence suggests that the role of electric buses in public transit is important if we are to take steps to reduce climate change and the environmental impacts of fossil fuels. Several electric alternatives are currently operationalized, and the debate about which is most suitable is attracting considerable attention. This article provides a detailed review of various performance features for three categories of electric buses: hybrid, fuel cell, and battery. Economic, operational, energy, and environmental characteristics of each technology are reviewed in detail based on simulation models and operational data presented by various scholars in different contexts. The study develops a holistic assessment of electric buses based on side-by-side comparison of 16 features that best inform the decision making process. The review indicates that the selection process of electric technology is highly sensitive to operational context and energy profile. In addition, it highlights that hybrid buses will not provide a significant reduction in GHG and would be suitable only for short-term objectives as a stepping-stone towards full electrification of transit. Battery and fuel cell buses are arguably capable of satisfying the current operational requirements, yet initial investment remains a major barrier. Overnight Battery Electric Bus is advocated as the most suitable alternative for bus transit contexts given the expected improvements in battery technology and the trend to utilize sustainable sources in electricity generation.

Contents

Abbreviations: ATR, Auto Thermal Reforming; CAGR, Compound Annual Growth Rate; CNGHEB, Compressed Natural Gas Hybrid Electric Bus; DHEB, diesel hybrid electric bus; FCEB, Fuel Cell Electric Bus; GHEB, gasoline hybrid electric bus; GSR, gas steam reforming; GREET, greenhouse gases, regulated emissions, and energy use in transportation; HEB, Hybrid Electric Bus; H_2-WE, hydrogen - electrolysis of water; MJ, mega-joules; NGSR, natural gas steam reforming; RED, renewable energy directive; UCs, Ultra Capacitors; TCO, Total cost of ownership; WTT, Well-to-Tank; BEB, Battery Electric Bus; CNGB, Compressed Natural Gas Bus; DB, diesel bus; EM, electric motor; GB, gasoline bus; GHG, greenhouse gas; H_2-NGSR, hydrogen - natural gas steam reforming; ICE, internal combustion engine; NGCC, Natural Gas Combined Cycle; PHEV, plugin hybrid electric vehicle; SD, single-deck bus; USC, Supercritical Steam Cycle; TTW, Tank-to-Wheel; WTW, Well-to-Wheel.

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1. Introduction

Initiatives to reduce transit emissions, the commitments associated with the Kyoto protocol and instability in oil prices are compelling policy makers to implement alternative technologies that will replace oil-dependent mobility. Despite significant efforts to enforce standards in order to reduce emissions generated from the traditional internal combustion engine, projected reductions are unlikely to meet the emission targets of the Kyoto protocol [1–4]. It is evident in the literature that alternative technologies are essential if we are to reduce the emission footprint of the road transport sector. Although, different technological solutions have been operationalized in recent years, oil-based mobility still holds the lion's share in the transport market and the market penetration of alternative technologies is still very small [3,5,6].

The implementation of new alternatives for road transport depends on various factors that are well addressed by the conventional petrol/diesel counterpart [7]. These factors involve, but are not limited to, energy logistics, cost-benefit assessment, infrastructure, and public acceptance. In this respect, public transit offers superior potential for considerable market penetration of alternative technologies, especially in the context of city buses [1]. Bus transit provides fixed routes, centralized depot locations, and shared infrastructure, among other factors, that are suitable for the implementation of alternative technologies. In such a context, the technology could be operationalized, tested, and optimized all the while reducing emissions [8]. Currently, several powertrains for urban buses have been introduced in the market. Each offers specific advantages that could be utilized to maximize emission reduction. However, selecting a suitable powertrain for each context depends on various factors such as cost, network structure, energy source, and driving conditions [1,9]. A trade-off between different features is required for optimal utilization of each technology.

There are several studies that model and quantify the techno-economic and environmental impacts of electric buses. These studies are mainly developed across three domains environmental, economic, and energy, which are thoroughly reviewed in the following sections. In a nutshell, environmental models investigate potential GHG emission reductions from electric buses [7,10–16], energy consumption models investigate energy efficiency of electric buses [9,11,17], and economic studies focus on the cost-benefit analysis of implementing electric buses in transit [9,18]. Other studies focus on the operational constraints of electric buses [1,16,19,20], and the perspective of stakeholders towards the implementation of electric buses in transit [21].

However, literature on electric buses is developed across many technical and non-technical disciplines as highlighted in Table 1. Several models and methods have been developed in different parts of the world, which are not necessarily linked in the literature [1]. It could be argued that the electric bus literature is fragmented; consequently there is a growing need for a comprehensive review of the literature, as well as, for developing a unified volume that combines reviews on both technical and non-technical aspects of electric buses. Some reviews of electric bus technology in transit have been developed to overcome this issue; Kühne [22] was among the early scholars to review the potential of electric buses in transit. His effort is followed by attempts to investigate the applications of electric buses in transit [23], and the market shares of electric buses across the world [24]. However, there is a lack of reviews that accommodate different powertrain configurations across a wide variety of technical and non-technical aspects.

This study builds on previous attempts and aims at providing a comprehensive review of electric bus features and their potential as a replacement for diesel buses in transit operation. Namely, the study focuses on Hybrid Electric Bus (HEB), Fuel Cell Electric Bus (FCEB), and Battery Electric Bus (BEB). Initially, an overview of the configurations of electric powertrains is provided. Market forecasts are illustrated in section three. A review of economic, environmental, operational, and energy features of electric buses is detailed in section four. Results are in turn utilized to generate a holistic comparison of electric buses, along with diesel, on 16 performance features of electric buses in section five. Lastly, a concluding section highlights the future on electric buses in transit operation, and presents avenues for future research.

2. Overview of electric buses technology

Electric buses operate by different degrees of electrification that depend on the configuration of the propulsion system [1,27]. These include, but are not limited to, Hybrid Electric (series and parallel), Fuel Cell Electric, and Battery Electric (overnight and opportunity) [7,28]. With the exception of parallel hybrid, all systems share a central concept that the propulsion energy is derived from an electric traction drive system. The main difference between these technologies is the power source for the electric engine.

Hybrid electric technology uses both an internal combustion engine (ICE) and an electric motor (EM), in various configurations, to provide wheels with traction power [27]. Hybrid buses are configured in two distinct forms: series and parallel. In parallel configuration, Fig. 1-a), both engines (ICE and EM) are connected to propel the vehicle. Traction power could be derived independently from the ICE and the EM, or through a combination of both. In series configuration, the on-board ICE, often referred to as generator, is used to generate electricity that is either transferred to the EM or stored in an on-board battery package as highlighted in Fig. 1-b) [27,29,30]. Several other configurations are available for hybrid buses that are based on the fuel source for the ICE, such as gasoline, diesel, natural gas, and biofuel [20]. Hybrid buses are often configured based on the required degree of hybridization [8,28,30]. High or low hybridization ratio refer to the energy output ratio from the EM and the ICE respectively [31]. The demands for a high hybridization ratio have led to the development of a plug-in hybrid technology [30]. Plug-in hybrid configuration follows series hybrid settings with an additional feature that allows the on-board battery to be recharged with an external electric source. This provides an electric only drive option without using the ice/generator for a limited range [30].

Fuel cell technology is an alternative method for the electrification of buses [32]. Fuel cell technology is based on powering the electric motor with electricity generated from fossil fuel.