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A review of Battery Electric Vehicle technology and readiness levels

Amin Mahmoudzadeh Andwari[a,b,*], Apostolos Pesiridis[a], Srithar Rajoo[c], Ricardo Martinez-Botas[d], Vahid Esfahanian[b]

[a] Centre for Advanced Powertrain and Fuels Research (CAPF), Department of Mechanical, Aerospace and Civil Engineering, Brunel University London, UB8 3PH, UK
[b] Vehicle, Fuel and Environment Research Institute (VFERI), School of Mechanical Engineering, College of Engineering, University of Tehran, Iran
[c] UTM Centre for Low Carbon Transport in Cooperation with Imperial College London (LOCARTIC), Universiti Teknologi Malaysia, 81310 Johor, Malaysia
[d] Department of Mechanical Engineering, Imperial College London, London SW7 2AZ, UK

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ABSTRACT

As concerns of oil depletion and security of supply remain as severe as ever, and faced with the consequences of climate change due to greenhouse gas emissions, Europe is increasingly looking at alternatives to traditional road transport technologies. Battery Electric Vehicles (BEVs) are seen as a promising technology, which could lead to the decarbonisation of the Light Duty Vehicle fleet and to independence from oil. However it still has to overcome some significant barriers to gain social acceptance and obtain appreciable market penetration. This review evaluates the technological readiness of the different elements of BEV technology and highlights those technological areas where important progress is expected. Techno-economic issues linked with the development of BEVs are investigated. Current BEVs in the market need to be more competitive than other low carbon vehicles, a requirement which stimulates the necessity for new business models. Finally, the all-important role of politics in this development is, also, discussed. As the benefit of BEVs can help countries meet their environmental targets, governments have included them in their roadmaps and have developed incentives to help them penetrate the market.

1. Introduction

Road based transportation accounts for a large share of Europe CO_2 emissions, 22% in the UK [1,2]. A growing concern about climate change triggered agreements between EU countries to cut their emissions by 80% by 2050 to stabilise atmospheric CO_2 at 450 ppm in order to keep global warming under 2 °C. The effort is shared between different sectors, and the road transport sector is expected to reduce its emissions by 95% [3–6]. Moreover, it is highly dependent on oil, which raises resource depletion and security of supply concerns. Lastly, urban pollution due to vehicle use causes health problems. This is why it is considered as crucial to develop low carbon and oil independent transport solutions [7–11]. Improvements in efficiency of current vehicles, biofuels and electric powertrains are three solutions being considered to tackle this issue. However as an increase in the number of passengers has been forecasted [12–14], total independence on oil and zero tailpipe emissions technologies will probably be needed in the long term [15–18].

Battery Electric Vehicles (BEVs) satisfy these two conditions. Their principle is simple: an electric motor powered by a battery replaces the Internal Combustion Engine Vehicle (ICEV) and the tank, and the vehicle is plugged to a charging spot when it is not in use [19–21]. They have many advantages: they are highly efficient, do not produce tailpipe emissions which is beneficial for local air quality, they have good acceleration, can be charged overnight on low cost electricity produced by any type of power station, including renewables [21–23]. However despite these advantages, BEVs, also, face significant challenges. Electricity storage is still expensive and the charging of the battery is time consuming; this is why the range of these vehicles is limited. A charging spot infrastructure must be in place before any

Abbreviations and acronyms: AC, Alternating Current; BEV, Battery Electric Vehicle; BMS, Battery Management System; CO_2, Carbon Dioxide; DC, Direct Current; DECC, Department of Energy and Climate Change; EPA, Environmental Protection Agency; EU, European Union; EV, Electric Vehicle; FCEV, Fuel Cell Electric Vehicle; FCHEV, Fuel Cell Hybrid Electric Vehicle; FCV, Fuel Cell Vehicle; GHG, Greenhouse Gas; ICE, Internal Combustion Engine; ICEV, Internal Combustion Electric Vehicle; IEA, International Energy Agency; kWh, kilowatt hour; LCA, Life Cycle Assessment; LDV, Light Duty Vehicle; Li-Ion, Lithium-ion; LPG, Liquefied Petroleum Gas; $Na/NiCl_2$, Sodium Nickel Chloride; Ni-MH, Nickel Metal Hydride; NOx, Nitric Oxide; PHEV, Plug-in Hybrid Electric Vehicle; PM, Permanent Magnet; ppm, part per million; SOx, Sulphur Oxide; USABC, United States Advanced Battery Consortium; USD, United States Dollar; VAT, Value-Added Tax; V2G, Vehicle to Grid

* Corresponding author.
E-mail address: Amin.Mahmoudzadehandwari@brunel.ac.uk (A. Mahmoudzadeh Andwari).

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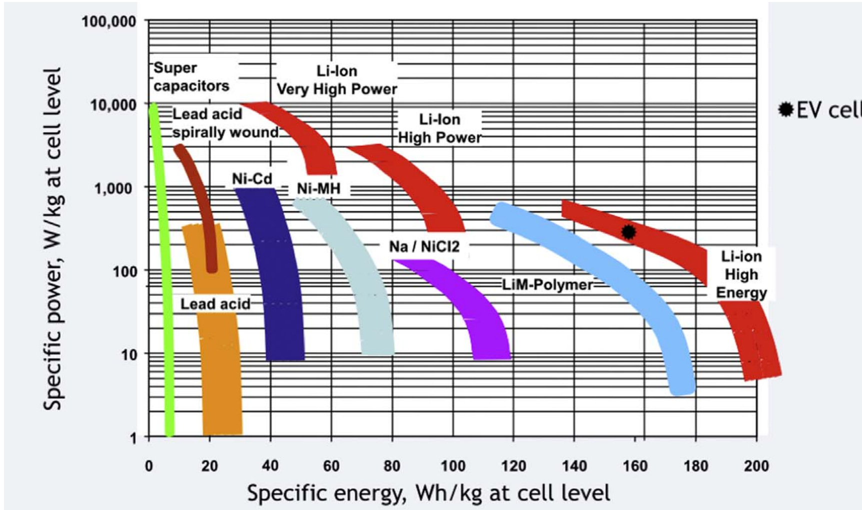

Fig. 1. Specific energy and power of the main battery technologies.

market penetration, and the corresponding investment is important. In addition, primary resource depletion concerns have been raised for some elements of the battery. The impact of BEVs on the grid could be damaging [24]. However, the most difficult issue is the social acceptance of these vehicles, which is the final great hurdle before BEVs can penetrate the market to any significant extent. Their high capital cost is a barrier for consumers and their low running cost has low visibility. The 'range anxiety' is probably the most important barrier: as the range is lower than for conventional vehicles, and charging takes time, consumers fear that they will not be able to complete their journey. This problem is exacerbated by the insufficient charging infrastructure [25–27]. However, most governments' roadmaps plan an important role for BEVs as they have a high potential for technological improvement. Moreover, new business models have been developed to compensate some of their disadvantages and policies have been implemented to support their development [28].

This review study aims to analyse the barriers for market penetration of BEVs, including social acceptance, and the solutions, which have been developed from the point of view of existing literature. Moreover the technological readiness of different components of BEVs is analysed along with their targets and their potential for development. In the meanwhile, the techno-economic issues linked with the development of BEVs and the business models, which have been designed as a solution to those problems, are presented and discussed. Lastly, the role of BEVs in the political roadmap-shaping is discussed which have already been taken or that can further be taken to support the increase of their market penetration.

2. Methodology

In this study through a previous literature review the barriers of market penetration of BEVs, including social acceptance, and the solutions, which have been developed are analysed. As the situation has evolved quickly in the last decade, it focused mainly on the publications of the past five years. It first analysed the technological readiness of the different components of BEVs, their targets and their potential for development. Secondly it studied the techno-economic issues linked with the development of BEVs and the business models, which have been designed as a solution to those problems. Finally, it determined the role of BEVs in government's targets and the measures, which have been or could be taken to support their penetration. In this work, a program is designed including three main goals, closely interlinked. The first one is to display the study of the technological and cost readiness levels of BEV components (based on the literature review), which are detailed in Section 3. The second one is to assess possible evolutions of this readiness up to 2050: a timeline and an evolution are added to the previous work; the assumptions necessary to build this projection are available in Section 4. The last goal is an assessment of the satisfaction of customers' needs and requirements in term of range, from a technological perspective.

3. Technological readiness of the components of BEV

3.1. Batteries

The technological readiness of batteries, the energy storage system of a BEV, is a crucial problem in the development and market penetration of BEVs. As the key component it is presented first in this section.

3.1.1. Key Requirements of the battery system

The key parameters for a comparison of batteries are the energy density, the power density, the cycle life, calendar life, and the cost per kWh [29]. Volume and safety are also mentioned. To a lesser extent, energy efficiency and self-discharge are also considered. Each technology and each battery is designed following a trade-off between energy and power density [30,31]. For BEVs the battery is generally sized by the energy requirements to allow a certain range to be reached [32].

It must be noted that the relationship between car range and battery capacity is not linear as the important additional weight of the battery (between 150 and 500 kg for a range of about 150 km) reduces the efficiency on the road. This is why it is important to compare batteries according to their energy and power densities.

Fig. 1 illustrates the range of specific power and specific energy for different battery technologies [33]. It can be noted that they differ greatly from one technology to another and that for a given technology the design allows for additional trade-offs between power and energy. United States Advanced Battery Consortium (USABC) has set a specific power goal of 150 kW/kg to allow long term commercialisation of BEVs, and a long term goal of 200 kW/kg [30]. It can be seen on the graph that the technology was still far of this goal in 2020.

The price of the battery represents an important share of the total cost of BEVs, which is why it is crucial to reduce it. The USABC evaluated the maximum price compatible with an important market share of BEVs was USD 150/kWh (with a long term goal of USD 100/kWh) [29]. International Energy Agency (IEA) estimated that in order for BEV to be competitive the battery prices would have to be under USD 300/kWh [34,35]. Fig. 2 shows the result of a price assumption for Li-ion batteries up to 2030 [36–38]. Technological improvements and breakthroughs are expected in this analysis, resulting in an