Materials Challenges for Electric Vehicles

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ABSTRACT

Electric vehicles provide the ability to substantially reduce or eliminate greenhouse gas emissions from transportation. Such vehicles utilize a fundamentally different powertrain technology compared to conventional vehicles based on the internal combustion of liquid fuels. In this series of articles, we discuss material challenges related to three key subsystems related to the powertrain of electric vehicles: batteries, power electronics, and permanent magnets. Given that electric vehicles currently occupy ~20% of the market share and are projected to rapidly rise, a cross-cutting challenge among these systems is the sustainability and resilience of the global supply chain of critical minerals to enable this adoption of electric vehicles.

INTRODUCTION

The world collectively produced about 85 million vehicles in 2022, including about 17 million in Europe and North America each and 50 million in Asia and Oceania[1]. Most of these vehicles are powered by an internal combustion engine (ICE) that utilizes petroleum-derived liquid fuels like gasoline and diesel. As a result, ground transportation accounted for about 18% of global CO_2 emissions in 2022, the third largest sector after power generation (39%) and industry (29%)[2].

Electrification, or the process of replacing the internal combustion engine with electric powertrains, represents the most promising avenue to de-carbonize the transportation sector. Because electricity can be produced from carbon-free sources including wind, solar, hydroelectric, and nuclear power, electrification provides an avenue to bring that carbon-free electricity to transportation. Compared to vehicles with ICE, electric cars offer a lower environmental footprint, with the total greenhouse gas emissions roughly halved (including production and consumption)[3]. For this reason, governments around the world have set ambitious targets for the widespread adoption of electric vehicles and its associated infrastructure like charging stations, manufacturing, and eventually recycling[3]. Beyond their environmental benefits, electric vehicles offer additional advantages for the consumer from faster acceleration, increased comfort, fewer moving parts, lower maintenance, to lower cost of energy and lower energy price volatility.

A SHORT HISTORY OF ELECTRIC VEHICLES

At the dawn of the automotive era in the late 1800s, many different powertrain systems were considered, with various power sources including petroleum, steam, and electricity. Electric vehicles, powered by lead-acid batteries, held distinct appeal with easy startup and lack of toxic fumes. In contrast, early vehicles with internal combustion engines required a hand crank starter and the manual changing of gears. Clara Ford, the wife of the automotive industrialist Henry Ford, preferred electric cars for their ease of operation[4]. Thomas Edison was an early proponent of electric vehicles (Fig. 1A), and sought to develop superior battery storage technology.

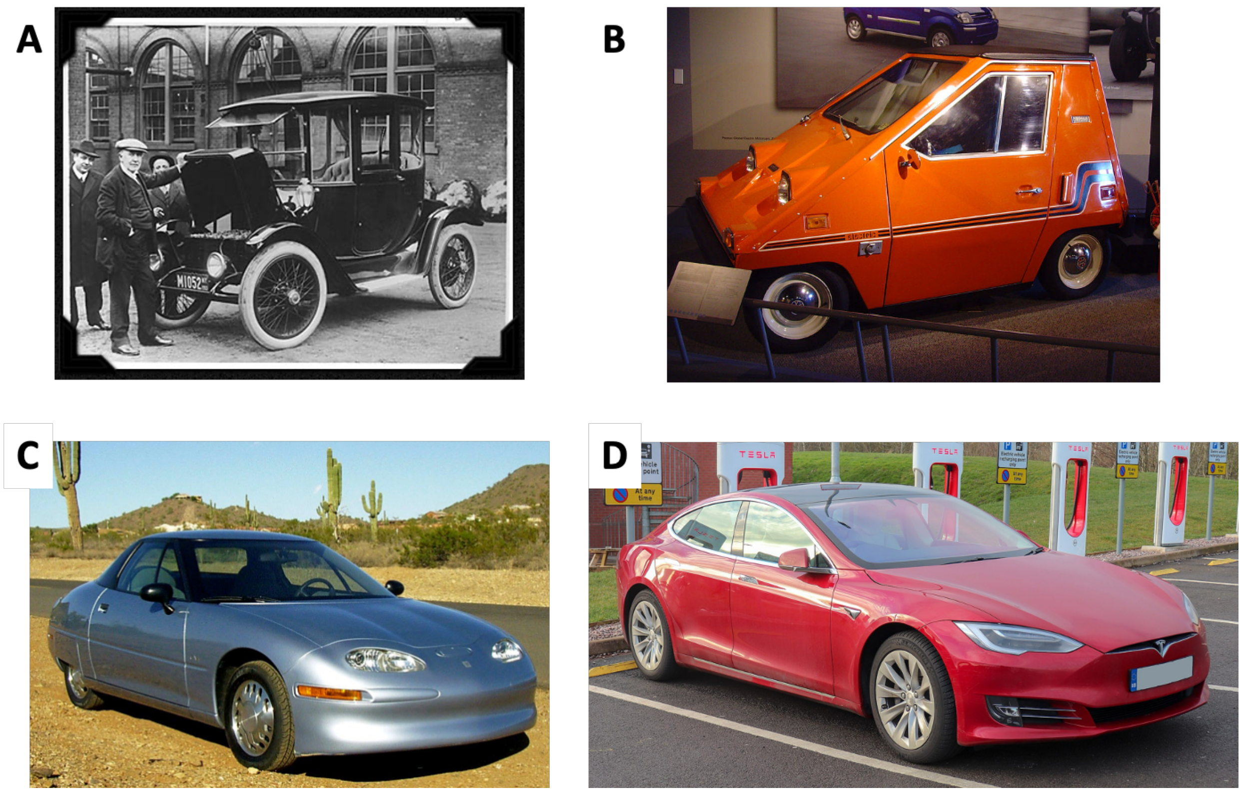

Figure 1: Historic electric vehicles. (A) Thomas Edison inpsecting an electric vehicle in the early 1910s. (B) Sebring-Vanguard Citicar from the mid 1970s after the first oil shock. (C) General Motors EV1 during the mid-1990s. (D) Modern Tesla Model S in the 2010s. Images from ref. [5–8]; images in public domain (A) or creative common attribution license (B-D).

Technological and societal developments soon resulted in the demise of these early electric vehicles. In 1911, Charles Kettering patented an electric "engine starting device" that replaced the hand crank[9], overcoming one of the key benefits of electric vehicles. Around the same time, mass production methods popularized by Henry Ford substantially decreased the cost of gasoline-powered cars, like Model T. Additionally, a network of refueling stations enabled internal combustion vehicles to be driven over long ranges, while highway systems started being developed around the world[10]. The continued discovery of new sources of petroleum in the interwar and postwar eras, including in the Middle East, ensured a plentiful supply of fuel for internal combustion engines.

Starting in the 1970s, three societal drivers led to renewed calls to challenge the reign of the vehicles with internal combustion engine. First, the oil shocks of the 1970s showed a critical weakness in nations that rely on petroleum from volatile international markets. This dependence became a reminder of the need for energy security and diversification. Second, tailpipe emissions became a primary source of smog and other air pollution in dense urban areas in both the developed and developing world. Finally, there was a growing realization that the burning of fossil energy results in CO_2 emissions – a primary driver of climate change. As a result, early production electric cars were developed by several companies, including the CitiCar, the most widely-produced electric vehicle in North America between 1945 and 2010 (Fig. 1B).

In the late 1990s, several automakers including General Motors and Toyota started to re-introduce electric vehicles in part to meet regulatory demands by the California Air Resource Board. While vehicles like the GM EV1 (Fig. 1C) and Toyota RAV4-electric gained popularity with early adopters, their short driving ranges, long charging times, and high initial costs were directly linked to the shortcomings of the lead-acid and nickel metal hydride batteries that were used to power them. These models were eventually scrapped as automakers and regulators looked to other means to reduce tailpipe emissions and improve fuel efficiency, including the hybrid-electric vehicle first introduced in the Toyota Prius in 1997. In parallel, in the early 2000s automakers and governments started to also explore the implementation of hydrogen fuel cell electric vehicles. An article[11] and a more comprehensive book[12] on electric vehicles were written by C C Chan in the early years of the millennium.

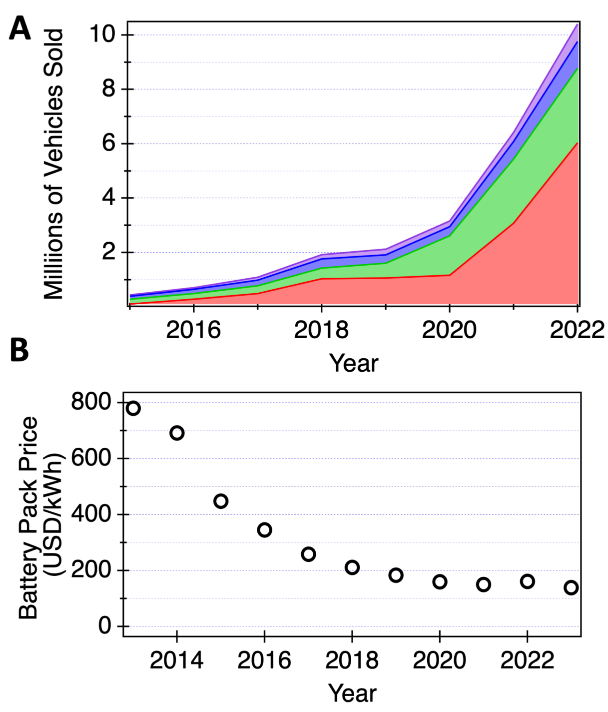

Fig. 2: Recent trends in (a) electric vehicle adoption and (b) battery pack price. Data from the Electric Vehicle Outlook Report from the Bloomberg New Energy Foundation[13].

The most recent push for electric vehicles occurred after 2000, driven by rising oil prices, concerns about energy security, and climate change. Around the same time, the Li-ion battery gained increased technological maturity and lower costs, driven by its widespread use in portable electronics since the debut of the Sony Camcorder in 1991. Around 2010, both established automakers and newer entrants like Tesla (USA) and BYD (China) started to introduce fully electric and plug-in hybrid electric vehicles, powered by Li-ion batteries (Fig. 1D). Prices of electric vehicle batteries have fallen substantially, enabling rapid increases in adoption (Fig. 2). In 2023, the global market share of these vehicles reached around 20%, including over 35% in China and 25% in Europe[13]. While the mass adoption of electric vehicles is widely considered an overall benefit for society and a critical step for climate change mitigation, it also introduces significant challenges, particularly in managing the complex supply chains required for their production and effectively addressing the growing volume of "dead" batteries at the end of their lifespans (second use and recycling). Developing efficient and environmentally friendly recycling processes for these batteries will be crucial to ensure the long-term sustainability of the electric vehicle development.

MATERIALS CHALLENGES FOR ELECTRIC VEHICLES

Automobiles are one of the most complex mass-produced products with a global supply chain. The key differences between electric and petroleum-powered vehicles reside in the powertrain. Fig. 3 provides a scheme of the power conversion processes in the powertrain of an electric vehicle. It consists of three subsystems – batteries, power electronics, and electromagnetic motors – each is of critical importance and is covered in the dedicated articles of this special issue.

The battery module is responsible for storing the electrical energy that powers the vehicle. Both Li-ion and post-Li-ion batteries and the design of their components have been the subject of intense research in recent decades. The second subsystem is power electronics for converting currents and voltages concerning both grid-to-battery charging and battery-to-motor propulsion. While traditionally such electronics were based on silicon, there has recently been substantial research and deployment of wide bandgap materials that yield higher performance. The final subsystem for electric vehicles is represented by the permanent magnet motors that transfer the electrical energy stored in batteries to mechanical energy to propel the car.

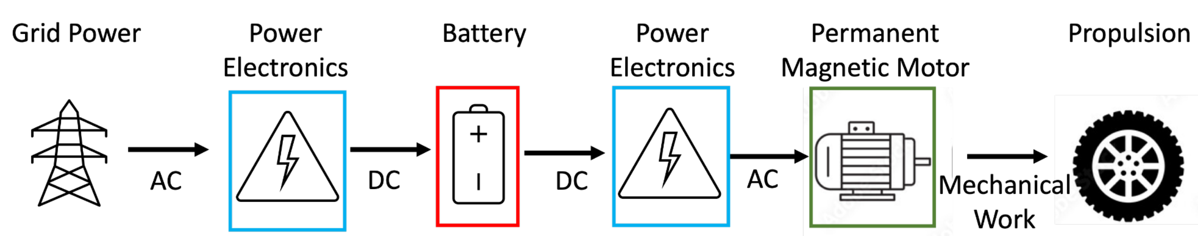

Fig. 3: Scheme of power conversion processes in an electric vehicle powertrain. This special issue contains articles from batteries, power electronics, and permanent magnets.

Development of the next-generation EVs requires continuous innovation in the interdisciplinary areas of materials and components that constitute and define performance characteristics of each of these subsystems. The goal of this special issue is to introduce readers to key concepts related to electric vehicles by explaining both existing and emerging technologies, overviewing their advantages and drawbacks, and illustrating how these technologies work together. We hope that it will provide researchers in the respective fields a more comprehensive understanding of the other systems and materials challenges that are highly relevant for next-generation electric vehicles.

PREVIEW OF THE TOPICS

The five perspective articles in this special issue are written by a diverse group of authors and institutions. They are intended to present an overview of the three key materials challenges with electric vehicles: batteries, power electronics, and permanent magnets.

The first article titled "Advancing electric mobility with lithium ion-batteries: A materials and sustainability perspective"[14] is written by Anika Promi, Katelyn Meyer, Rupayan Ghosh, and Feng Lin from Virginia Polytechnic and State University (Virginia Tech). This article introduces the global landscape of lithium-ion batteries from the materials science perspective, examining both the functionality of batteries and the challenges associated with design of cathode and anode materials. Recognizing the current geopolitical landscape, the authors emphasize the importance of sustainable and resilient supply chains for the critical minerals used in these batteries. This analysis is crucial for researchers and engineers developing next-generation electric vehicles.

Focusing on sustainability and supply chain resilience, the second article is titled "Garbage In, Metal Out: A Perspective on Recycling Battery Metals Using Organic Molecules"[15], by Pouria Akbari, Abbey E. Strohmeyer, Douglas T. Genna, and Jeremy I. Feldblyum from the University of Albany and Youngstown State University. This article discusses current and emerging approaches for end-of-life batteries, thereby targeting the separation and extraction of critical minerals like Li, Co, Ni, Mn, and Cu from the battery waste. This article starts by reviewing hydrometallurgical and pyrometallurgical approaches using strong acids and high temperatures, before diving deeper into more sustainable and emerging pathways based on more benign organic acids.

The third article explores the potential of solid-state batteries for next-generation EVs. By replacing the flammable liquid electrolyte with a solid ion-conducting electrolyte, solid-state batteries can potentially yield batteries with higher energy densities and safety. Titled "Manufacturing and Characterization of Solid-State Batteries for Electric Vehicle Applications", Eric Kazyak from the University of Wisconsin and Regina Garcia-Mendez from Johns Hopkins University presents an overview of the materials and manufacturing challenges of solid-state batteries[16].

The fourth article titled "(Ultra) Wide Bandgap (UWBG) Semiconductors for Electric Vehicles" by Geetak Gupta (Transphorm Inc) and Elaheh Ahmadi (University of California, Los Angeles) overviews consideration for wide bandgap material design that are necessary for both the charging of electric vehicles and the conversion of battery power to electric motor power[17]. Gupta and Ahmadi first present the half-bridge, a representative DC-DC power conversion circuit that illustrates the requirements for efficient power electronics. They then introduce how wide bandgap materials such as silicon carbide, gallium nitride, and gallium oxide that can enable significantly higher efficiency, and reduced thermal losses, compared to traditional silicon-based power electronics. This can potentially translate into substantial advancements for EV charging infrastructure and the conversion of battery power to propel the vehicle's electric motors.

Finally, Chris Rom, Sita Dugu, Shaun O'Donnell, Rebecca Smaha, and Sage Bauers from the National Renewable Energy Laboratory present "Established and Emerging Magnetic Materials for Electric Vehicle Motors."[18] These motors rely on permanent magnets to enable the efficient transduction of electrical energy (supplied by batteries and converted to AC using power electronics) to mechanical energy. Traditionally, these magnets are composed of rare-earths metals like neodymium-iron-boron and samarium-cobalt. This article first overviews these traditional materials before focusing on challenges and opportunities for earth-abundant permanent magnets, like iron nitride and iron nickel alloys.

PERSPECTIVE

Electric vehicles are a mature and deployed technology with widespread adoption. While many of the initial challenges to enable functionality, scaling, deployment, and manufacturing have been solved, dramatic growth of EV industry resulted in new challenges in particular concerning to mineral abundance, sustainable manufacturing, and supply chain resilience amid geopolitical tensions. Consequently, this issue delves into the materials science challenges that arise from the significant scaling of EV production.

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AUTHOR CONTRIBUTIONS

Both authors jointly wrote and edited this article.

CONFLICTS OF INTEREST

The corresponding authors state that there is no conflict of interest.