Advanced materials supply considerations for electric vehicle applications

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Electric vehicles are now proliferating based on technologies and components that in turn rely on the use of strategic materials and mineral resources. This review article discusses critical materials considerations for electric drive vehicles, focusing on the underlying component technologies and materials. These mainly include materials for advanced batteries, motors and electronics, lightweight structures, and other components specific to each vehicle type. Particularly strategic and widely used minerals and elements/structures for electric vehicles include nickel, cobalt, rare-earth minerals, lightweight and high strength steel alloys and underlying metals (e.g., magnesium and aluminum), carbon fiber, graphite and graphene, copper, and steel alloying materials. Additional key considerations include those around component and vehicle supply chains, repurposing and recycling vehicle components at end of vehicle life, and environmental and humanitarian considerations around the extraction and transport of the evolving set of materials needed for modern electric vehicle production.

Introduction

After many years of development, electric vehicles (EVs) are now being adopted in many countries with expected further growth in market share, perhaps becoming a dominant drivetrain option for light and heavier vehicles by around mid-century. EVs come in several types, ranging from those that are completely battery powered to those that are plug-in hybrids (PHVs), that can be differentiated as having serial or parallel electric/gasoline drivetrains, and fuel cell vehicles (FCVs) that mainly rely on hydrogen fuel cells for power but also include battery storage systems. FCVs use similar drive motors and power electronics to battery EVs and serial PHVs, being fully electrically powered, but also include additional components related to the fuel cell system and hydrogen storage.

EV market developments are being supported by governments and public agencies because they are considered a leading option in transportation to reduce emissions of greenhouse gases (GHGs) and other harmful products of the use of fossil fuels in combustion engines. In tandem with reduced emissions from the power sector, EVs can become more low emission over time and can also integrate with utility grids to help further introduce renewable energy sources. **Figure 1** shows

a diagram of a modern EV architecture and the major system components.

This review article discusses critical materials considerations for EVs, PHVs, and FCVs, focusing on the underlying component technologies and materials. These mainly include materials for advanced batteries, motors and electronics, lightweight structures, and other components specific to each vehicle type. Particularly strategic and widely used minerals and elements/structures for EVs include nickel, cobalt, rare-earth minerals, lightweight and high strength steel alloys and underlying metals (e.g., magnesium and aluminum), carbon fiber, graphite and graphene, copper, and steel alloying materials such as vanadium and zirconium.

Following a discussion of general considerations for advanced materials for EVs, the paper next discusses the specific materials considerations of various types of advanced EV batteries, now heavily employing lithium-based chemistries. Next, the paper discusses key materials considerations around lightweight structures and components. The paper then includes a discussion of materials specific to hydrogen fuel cell vehicles, including those related to fuel cell systems and hydrogen storage tanks. The paper then discusses overall EV materials supply chain and recycling considerations.

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Figure 1. Cutaway diagram of modern EV showing battery pack (middle), electric drive motor (rear), and power electronics and radiator/cooling system (front). Source: Audi AG.

Finally, the paper concludes with overall findings and critical research and development needs and opportunities for advanced materials.

General considerations for advanced materials supply for EV applications

Electric drive vehicles use a range of materials that differ markedly from the materials used in modern internal-combustion engine vehicles. These include materials used in EV batteries, drive motors, power electronics, and, in the case of fuel cell vehicles (FCVs), also the fuel cell stack, auxiliary systems, and high-pressure hydrogen storage tanks. Key materials consideration especially include those for lithium, cobalt, and nickel for advanced lithium-ion batteries, as well as “rare-earth” metals such as neodymium, samarium, and dysprosium for advanced electric drive motors. Modern EVs also may use significant amounts of carbon fiber and other lightweight materials in their structures as well as in other components, such as carbon fiber wrapped metal hydrogen storage tanks for FCVs.

Global demand for these materials is expected to increase markedly in the coming years, with expected expansion of EV markets. For example, global demand for lithium for EV batteries has recently been estimated at about 300,000 metric tons, compared with global production at 520,000 metric tons.¹ However, demands for lithium for EV batteries could reach 2.8 million metric tons by 2028 by one forecast, outstripping projected mining capacity of about 2 million metric tons.¹ By 2100, demands for new lithium resources could be in the range of 4.4 to 7.5 million metric tons, where availability of material could be a major constraint.² Thus, near-term, it is only mining capacity rather than overall lithium availability that is at issue. But later in the century, the actual availability of lithium at economical prices could be a concern with billions of EVs produced and even with recycling of materials from spent EV batteries.^{2,3}

In any event, the extraction, refining, and use of the various materials used in modern EVs involve complex interactions through associated industries and global trade, flowing up to supply chains of then manufactured components for use by automotive original equipment manufacturing companies (OEMs). With regard to the key element of lithium, used in all of the EV battery technologies discussed here, the element in its most extractable forms is not well distributed globally and thus subject to key materials supply constraints. Most global deposits are in brine locations (estimated at 83% of reserves), largely in South America but also in China and the United States, while smaller amounts (17%) are in hard rock in the form of mineral deposits, especially in Australia.⁴ Lithium is also present in large quantities in seawater, but in levels too low for economical extraction compared to other types of reserves.

Problematically, some of the most mineral wealthy countries have political and economic instability. Afghanistan for example, has vast natural resources relevant to advanced energy technologies, including cobalt, copper, iron, gold, silver, rare-earth minerals, lead, chromium, and lithium in hard rock form. China has vast rare-earth mineral resources but is not otherwise particularly resource abundant except for coal, while Russia possesses large amounts of iron, manganese, chromium, nickel, platinum, titanium, copper and other strategic metals and minerals. There are complex strategic, logistical, and geo-political issues around extracting, refining, manufacturing and assembling EV components based on these materials.

A key emerging issue now that EVs are being commercialized in large numbers is the recycling and re-use of key materials. Closed loop manufacturing cycles including large-scale recycling of spent batteries and other key EV components will be important to reducing reliance on virgin materials, that are sure to be increasingly harder to obtain over time as the richest and most easy to produce resources are expended first.

Materials considerations for advanced electric vehicle batteries

Over the past decade, improvements in lithium-based batteries coupled with declining costs have made them the dominant choice for EVs. Previous generations of EVs and hybrid vehicles employed nickel-metal hydride, lead-acid, nickel-cadmium, and other battery types, but these have almost entirely given way to various types of lithium batteries in modern EVs. There are several types of lithium batteries, based most fundamentally on varying cathode materials, but also potential anode materials as alternatives to the conventional graphite. Primary lithium-ion types include lithium cobalt oxide (LCO), lithium manganese oxide (LMO), lithium nickel manganese cobalt oxide (NMC), lithium iron phosphate (LFP), lithium nickel cobalt aluminum oxide (NCA), and lithium titanate (LTO). These involve different uses of basic materials, with use of cobalt of particular concern given its relatively high cost and concerns about human rights associated with mining

practices, as well as use of nickel that is also relatively expensive in the processed form needed for advanced EV batteries. **Figure 2** indicates basic materials breakdowns for some of the lithium battery chemistries discussed in this section.

LCO is a well-established battery chemistry based on LiCO_2 , dating back to about 1980 and still in wide use especially for portable electronics. It has properties of high energy density, high cycle life, and good overall reliability, but includes intensive use of cobalt as well as lithium. It also suffers from physical cell degradation at high operational voltages such as through surface degradation, phase transitions, and inhomogeneous reactions.⁶ One production method for LCO is to co-precipitate Co^{2+} and $\text{C}_2\text{O}_4^{2-}$ solutions, yielding solid rods of CoC_2O_4 that are used with water in a calcination step to develop what is known as an interconnected LCO. This LCO material can then be soft milled into discrete sub-micrometer sized LCO particles for use battery cathode materials, with enhanced discharge/rate and efficiency performance of materials as well as greater simplicity of process steps compared with some other fabrication methods.⁷

Batteries based on LMO cathodes use manganese-dioxide (MnO_2) as the basic material, with advantages of employing earth-abundant and non-toxic materials. LiMn_2O_4 is a well-established LMO formulation, with several different compounds designed to manage the relative drawbacks of LMO including physical degradation due to dissolution of electrode material. This especially occurs when the oxidation state of manganese drops below $\text{Mn} + 3.5$, tending to form Mn(II) and Mn(IV) , where the Mn(II) can then dissolve into most types of electrolytes and this then degrades the cathode.⁸ Hence, efforts have focused on maintaining magnesium oxidation states above +3.5 during battery operation using various spinel, layered, and composite concepts for electrode design.

Meanwhile, NMC battery cathodes (LiNiMnCoC_2) are now among the most widely used for transportation

applications of lithium batteries, dating back over 10 years and incorporating both cobalt and manganese along with lithium and nickel. They have high specific energy and good all-around battery characteristics including specific power, lifetime, and safety. Industry product offerings reveal typical NMC cathode powders consisting of 33% nickel, 33% manganese, and 33% cobalt, referred to as a 1-1-1 blend, designed to reduce manufacturing costs relative to higher cobalt levels. Recently, a new advanced battery called NMC 811 has been announced with cathode material content of 80% nickel, 10% manganese, and only 10% cobalt, a potential “game changer” for the industry depending on how it performs in the real world. At least two major automakers have announced plans to introduce these new NMC 811 batteries in upcoming models.

LFP (LiFePO_4) based batteries are also widely used, incorporating iron and phosphate and avoiding the use of nickel and cobalt in the cathode. These batteries are less energy dense than nickel-based designs but are stable and considered ideal for stationary applications especially. Industry information shows cathode powder formulations that are coated with carbon, known as C- LiFePO_4 , with weight compositions (not including oxygen) of about 4% lithium, 32% iron, 20% phosphorus, 0.3% manganese, a trace of lead, and about 1.5% carbon for particle coating. Interestingly, EV industry leader Tesla has recently indicated a switch to LFP type batteries after incorporating mostly NCA types in the past.

The NCA type batteries are fundamentally based on nickel, cobalt, and aluminum for the cathode material, with formulations such as $\text{LiNi}_{0.8}\text{Co}_{0.15}\text{Al}_{0.05}\text{O}_2$. These have the advantages of relatively low usage of cobalt and good energy density and have been used in commercial EVs including most Tesla vehicles produced to date. Investigations are continuing to explore advances in producing the cathode powders and full electrodes for better overall performance, using a variety of techniques. These include solid-state reaction, solution combustion, atomization, spray drying, and infrared methods for NCA precursor fabrication, and various further advanced techniques for electrode manufacture.⁹

Lithium-titanate-oxide or LTO batteries ($\text{Li}_4\text{Ti}_5\text{O}_{12}$) are another type, dating back about 15 years. These are characterized by fast-charging capability, long cycle life, and generally good environmental characteristics, but considerably lower energy density than most other lithium battery types. This is primarily owing to the lower fundamental cell voltage of 2.4 V for this battery chemistry compared to 3.6 V for most other lithium battery types.

Figure 3 presents a general materials composition for a modern EV battery, including active and passive battery materials. These include cathode, anode, and electrolyte solution materials, as well as structural materials including separator plastics, aluminum and copper current collectors, and carbon black and binder materials.

Figure 2. Primary materials requirements for lithium-ion battery types (kg/kWh). Source: From data presented in Reference 5.

This discussion highlights the importance of cathode materials in the overall lithium battery story, whereas battery anodes are somewhat simpler and typically comprised carefully formed graphite owing to its many benefits for this battery type. Graphite (either naturally or synthetically formed) has the characteristics of having high capacities for lithium-ion acceptance with low volumetric expansion, along with high reversibility, good cycle life, and good electronic conductivity.¹⁰ For enhanced capacity, graphite anodes can be comprised individual layers of graphene that are stacked together, allowing for spaces for the lithium ions to be intercalated. Recent investigations include addition of silicon to the anode, attempting to take advantage of its very high capacities expressed in mAh/gram. However, these Si-based materials are subject to high volumetric expansion and thus the levels for practical batteries at present appear to be limited to about 5% silicon by weight.¹⁰

Finally, another key component of lithium-based batteries is the separator material that is sandwiched between the positive and negative electrodes and that acts as a Li^+ ion conductor. The characteristics of these materials can affect cell performance, longevity, manufacturability, and recyclability. The material is typically a synthesized plastic type of material, with various types such as polyethylene, polypropylene, polyolefin, and poly(vinylidene fluoride) being used and investigated as separator materials.¹¹

Further in the future, a new class of lithium battery being developed that is known as solid-state. It employs a solid rather than gel type electrolyte, with potential benefits for safety, temperature tolerance, and energy/power density, as well as possible use of metal rather than graphite anode materials. Exploration of a variety of separator materials includes inorganic and organic electrolytes, as well as composite electrolytes based on ceramics and polymers blended together to compensate for shortcomings in the more basic types.¹² Solid-state lithium batteries seem poised to be the next frontier in EV battery technology, with the entire industry potentially affected as a result of these emerging market developments.

For further discussion of battery materials considerations for additional battery types, please see Gür¹³ in this volume. This includes those being developed and deployed for electrical utility grid and other energy storage applications as well as the EV batteries discussed here.

Materials for electric vehicle motors and electronic components

Of course, EVs have entirely different propulsion systems (electric motors vs. combustion engines, both with associated transmissions) than conventional vehicles, separate from the battery power system. The key component for EVs is the electric drive motor, consisting of a single moving part (the rotor) compared with hundreds of moving parts in a modern

combustion engine. For EV applications, there are several potential candidates for motor technology including direct current (DC), alternating current (AC) induction, brushless permanent magnet (BPM), and switched reluctance motors, among others. Also, EVs can have one motor (front or rear wheel drive), two (one motor for each axle), or four (one motor for each wheel). The only commercially deployed motor types at present are BPM and AC induction motors, where most automakers employ BPM but Tesla and a few others have historically used AC induction, with Tesla recently adopting BPM technology for the smaller Model 3.

These motor types differ markedly in that AC induction motors do not rely on rare-earth magnet materials but also have some performance limitations compared with BPM motors. Rare-earth materials are a group of 17 lanthanide group elements (also including yttrium and scandium), of which samarium and neodymium have been primarily used as advanced magnet materials. Now, neodymium iron boron (NdFeB) is the dominant type of BPM motor material, representing the most powerful commercially available magnet material.

Figure 4 presents the geographic distribution of rare-earth materials across the globe. They are generally well distributed compared to other strategic EV materials such as lithium and cobalt, but the richness of ores for these various materials varies greatly across deposits, with many having only low levels of the most useful and costly elements. Based on current levels, China controls a large amount (80%) of commercial rare-earth metals production, but other countries including the United States, Australia, and others are capable of developing reserves that could change this supply situation.

BPM motors have higher peak and overall efficiencies and power densities compared with AC induction motors but suffer from loss of magnetism at higher temperatures, a feature that must be managed in EVs with effective cooling strategies. Whereas AC induction motors use copper windings on both the rotor and stator to generate an electrical field, BPM motors use stationary magnets in the rotor coupled with copper windings in the stator. **Figure 5** shows a drawing of a modern BPM EV motor and motor assembly as used in the General Motors

Figure 5. Electric motor system design for a modern Chevrolet Bolt electric vehicle (149 kW nominal rating). Source: General Motors.

Figure 4. Geographic distribution of known rare-earth material deposits. Source: Reference 14.

Chevrolet Bolt vehicle, nominally rated at 149 kW of power and 360 Newton-meters of torque.

EVs also employ sophisticated power electronics and motor controllers in the propulsion system, consisting of complicated networks of copper wiring, a DC to AC power inverter, and computerized electronic controls. Industry statements by Tesla indicate the Model S employed about 3 km of wiring, while this was reduced to about 1.5 km in the Model 3 with plans to further reduce in the future. The central power-inverter switching components for EVs employed metal oxide semiconductor field-effect transistor (MOSFET) technology in earlier years but now are largely incorporating a closely related insulated gate bipolar transistor (IGBT) technology. The various intricately manufactured electronic devices in the overall motor controller system are composed mostly of basic materials such as copper, steel, silicon, and plastic, but also potentially with small amounts of rarer materials such as gallium. They are currently limited by manufacturing rather than basic materials constraints, where in recent years availability of microchip components in particular has been a constraint on production for some vehicle manufacturers.

Lightweight materials and structures

Lightweight materials for EVs are discussed in this section, focusing on magnesium, aluminum, and titanium metal alloys and high strength steels as well as composite and more complex materials. This section focuses on materials for the body structure of the car. These include multi-material, body-in-white designs (see different concepts in **Figure 6**) as well as the battery housing and support structure.

Magnesium alloys possess the lowest density among all structural materials, and with other additional advantages including high strength-to-weight ratio, good castability, deformability, recyclability and high damping capacity, application in the automotive area directly leads to weight reduction and efficiency improvements. Brief reviews of historical trends in vehicle weight and automotive magnesium, key barriers to wider adoption of Mg in high-volume vehicle applications, and promising paths of manufacturing and processing for this material are provided in References 15 and 16. The die-cast cross car beam of the type by GF Casting Solutions shown in **Figure 7** offers many advantages for manufacturers of light vehicles. Cast Mg can replace many individual steel sheet parts or profiles. With a complex casting solution maximum functional integration and a significant weight reduction can be achieved.

Figure 6. Different concepts for body-in-white design include (a) Mach-II body-in-white design by Ford heavy on magnesium, with permission from Ford Motor Company, (b) full battery electric Volvo XC40 heavy on steel, with permission from Volvo, and (c) Lightweight Multi-Material-Body-Concept for an EV heavy on aluminum, with permission from Volkswagen Aktiengesellschaft.

Figure 7. Die-cast cross car beam made of magnesium, with permission from GF Casting Solutions AG, Switzerland.

Figure 8. Comparison of mass savings in automotive applications for advanced materials vs. mild steel in structural panels for equivalent bending stiffness and bending strength, based on Reference 23.

Figure 8 shows that the mass saving potential of magnesium is slightly higher than aluminum and significantly higher than polymer and glass-fiber-reinforced plastic materials. However, in a cost-sensitive market, wrought magnesium must show some clear advantages and can only be competitive when its cost is close to that of aluminum sheet. Trang et al.¹⁷ report an alloy design concepts that can simultaneously provide high strength and good formability. The concept is based on the utilization of alloying elements that can induce precipitation, as well as maximize the segregation of other texture-controlling alloying elements. The increase in strength and ductility, that is necessary for many applications, can be obtained by either processing followed by extrusion with equal-channel angular pressing (ECAP), as well as grain refinement.^{18–20} The potential to develop high strength low-cost wrought magnesium alloys through precipitation hardening is very high and discussed in References 21 and 22.

Figure 9. Mechanical properties of Mg-Li alloys in comparison with commercial alloys, based on References 24, 30–37.

Magnesium alloys range from alloys of very low density, Mg-Li based alloys to alloys of higher density, like Mg rare-earth (RE) alloys. Results of recent scientific investigations have yielded insights into the structure and behavior of these materials. **Figure 9** shows the yield strength and elongation of Mg-Li alloys compared to commercial alloys. Additions of Al, Zn, Cd, and Ag providing the greatest strengthening effects.²⁴ A study on binary Mg-Li alloys has indicated that alloying 5 wt% lithium exhibited a low degree of dynamic recrystallization (DRX) compared with 1 and 3 wt% lithium and stronger prismatic texture resulting in higher mechanical strength and low elongation along extrusion direction.²⁵ Regarding corrosion behavior, work by You et al.²⁶ reviewed recent research and developments on wrought magnesium alloys from the viewpoint of the alloy design, focusing on Mg-Al, Mg-Zn and Mg-RE systems. Along with improving strength by solid solution strengthening and precipitation hardening,^{27,28} RE

additions, such as Gd, Y, Nd, Dy, Ho, Er, Ce, La, and Yb, can significantly improve the deformability and other structural characteristics of Mg.²⁹

Precipitation hardening in Mg-Y-Nd alloys is very effective with finely dispersed particles, also acting positively on corrosion properties.³⁸ Grain growth during ageing is not significant in Mg-Y-Nd-Gd-Dy alloys. As a representative coating that improves the corrosion behavior of Mg alloys to fit the respective vehicle applications, plasma electrolytical oxidation (PEO) coating is highlighted. PEO coating on sheet AM50, AZ31 and E-Form® plates, and other alloys, which are already used in the automotive industry, show that high-resistance low-porosity PEO coatings can be adapted to any Mg alloy.³⁹

By means of the different alloy types and their wide range of mechanical and technological properties, aluminum alloys are the most important design materials with good formability (extrusion, deep-drawing), machinability, weldability, and very good corrosion resistance. Mechanical properties of these materials can be applied similarly as with Mg alloys. In the 6061 Al alloy, for example, the precipitation hardening is based on the strengthening phase Mg₂Si and ECAP, even the application of post-ECAP aging leads to additional improvement.⁴⁰ Even aluminum alloys form a natural passive layer, however, and the composition and reformation of this layer during cathodic polarization is of interest in alloy development. Challenges and demands of future fuel-efficient vehicles are presented in the study by Liu et al.,⁴¹ including the use of barrier coatings for corrosion and defect site protection.

Aluminum consumption will increase in electric vehicle in the coming years, not only in extruded body parts, but also in battery containers. The aluminum case guarantees lightness and shock resistance and supports the battery temperature management system with its high thermal conductivity. Finite element optimization software is often used in the design process to increase stiffness and reduce noise.⁴² In modern EVs, there are high-pressure die-castings used in battery housing.⁴³ These include for example, AlSi10MnMg or AlSi7Mg, as well as joined multi-layer sheet metal, where some already have

integrated cooling functions.⁴⁴ Also, innovative sandwich materials made of aluminum face sheets and a core of aluminum hybrid foam are used for the battery housing as shown in **Figure 10**, focusing on compression strength and specific deformation energy absorption of the core layer material.

For completeness among the group of lightweight materials, titanium alloys can be regarded as a highly interesting structural material for lightweight construction. These alloys have relatively low density, high strength, low thermal expansion, and high corrosion resistance. However, titanium alloys are unlikely to be used in mass-produced automotive parts as they are generally too expensive. Applications such as fuel cell stacks may use titanium due to its high strength to weight ratio and superior corrosion resistance under extremely severe conditions.⁴⁵

Thus, when single homogeneous materials cannot meet overall design requirements, such as in some EV components, multi-material composites can be used to develop targeted materials for specific applications.⁴⁶ One example is high strength steel, a class of low-carbon (<0.25% content) steel with use of many potential alloying metals. These can be classed as lightweight materials due to their high specific strength relative to more typical carbon steel. Moving forward, both polymer-based as well as metal matrix composites are likely to be utilized for high strength steel for EV body-in-white and other structural elements.

The design and development of highly integrated lightweight structures is also improving, focusing on very lightweight and high strength structures such as sandwich designs.⁴⁷ Türk et al.⁴⁸ investigated design potentials where the combination of additive manufacturing and carbon fiber prepreg technology is applied to honeycomb sandwich structures. Significant weight savings and parts reduction indicate that the technology is competitive for complex low volume parts. Complex integral design combines the positive features of differential and integral design; using fewer subcomponents, the amount of interface is reduced, which leads to reduced notch effects and corrosion

Figure 10. Battery housing pack: (a) as an integral part of the “body in white” and (b) made of a hybrid foam sandwich. Source: Fraunhofer IFAM, Bremen, Germany.

between parts of different materials.⁴⁹ The combined approach has gained entry into the product architecture of EVs.^{50,51}

Although fiber-reinforced plastics are increasingly being used in lightweight automotive construction, metals will retain their primary importance as they are still easier to manufacture using conventional and less expensive processes. While the circumstances will continue to be competitive, some metallic parts in lightweight constructions will not be able to be replaced due to their demanding requirements, for example high strength steels. Also mentioned should be the good deformation behavior of appropriately alloyed and treated metals, which can be used to absorb kinetic energy in the event of a crash. Even in the case of fiber-reinforced car bodies, a metallic basic structure will likely still be employed in future EV designs.

Hydrogen fuel cell system materials

As an emerging technology for transportation applications, hydrogen fuel cells provide an alternative power system for EVs to those that are solely based on storage batteries. Fuel cell-based drivetrains for vehicle as currently using proton-exchange membrane (PEM) fuel cell systems. This type of fuel cell operates at relatively low temperatures of around 85°C and below, lending itself to intermittent operation. Other types of PEM fuel cells operate at temperatures somewhat above 100°C, with somewhat different membrane types, known as high-temperature PEM or “HT-PEM,” but these types of fuel cells have yet to be employed in automotive applications.

The PEM fuel cell unit in a vehicle is an assembly that consists fundamentally of a stack of repeat cell-level units to accumulate meaningful electrical voltages. Each stack may have some hundreds of cells, stacked together in a prismatic fashion. The critical component in each cell is known as a membrane-electrode assembly or MEA, which consists of sandwiched layers of material around the central sulfonic acid membrane. During PEM system manufacture, the MEA material is stacked in layers in unit cell elements along with

bipolar plates that act as both gas manifolds and current collectors. These bipolar plates are typically manufactured out of graphite, graphite composite, or high strength steel materials. The fuel cell system also includes balance-of-plant components, mainly consisting of gas manifolds, an air compressor, an anode gas recirculation pump, and a radiator cooling system with associated pumps and valves.

Every fuel cell system for motor vehicles also includes a storage battery, to provide for regenerative braking and additional power to assist the fuel cell during high power driving modes. Some earlier FCVs employed nickel-metal hydride batteries, but now lithium-ion batteries are the dominant choice. For example, the second-generation Toyota Mirai FCV includes a relatively small 1.24 kWh battery pack operating at 311 V, along with a PEM fuel cell system rated at 128 kW.

Most of the materials and components used in PEM fuel cell systems are relatively common, based on steel, metal alloys, and graphite. However, exceptions include the platinum and other precious metal catalyst material, the sulfonic acid membrane material, and carbon fiber used in the high-pressure hydrogen storage tanks. Also, special grades of stainless steel (e.g., grade 316) are needed for best compatibility with hydrogen piping and fittings, to avoid issues with hydrogen embrittlement of more common types of steel.

The most expensive and strategic material used in PEM fuel cells is platinum, potentially used with other precious metals such as ruthenium and rhodium. These can be used as catalyst materials on both the positive and negative electrodes. One analysis suggests that future demand of platinum for FCVs could increase the price (based on supply and demand economics) such that by 2050 if FCVs reach 40% of light-duty vehicle sales, this increased demand could help drive platinum prices up by about 70% compared to 2010 levels. However, catalyst loadings on the cell electrode layers are estimated to have a 90% potential for declines in this same period, suggesting overall decreases in catalyst cost on a per-vehicle basis.⁵² PEM fuel cells may also employ mixes of

Figure 11. Proton-exchange membrane (PEM) fuel cell unit cell design (a) and general schematic of operation (b). Source: Reference 55.

platinum with ruthenium, rhodium, or other precious metal catalyst materials, also being costly and strategic but that can reduce the reliance on platinum.

As an additional consideration, the sulfonic acid for PEM fuel cell membranes is a class of substance known as a perfluorinated polymer material, commercially sold as a resin for coating of fuel cell membranes. Nafion™ and Gore® are two major types of these membranes, now being produced in large quantities for use in multi-layer MEAs. While higher temperature PEM-type fuel cell membranes are being developed, conventional membrane materials are limited to temperatures below 100°C, where membrane degradation occurs above these temperatures.⁵³

The PEM fuel cell MEA materials are relatively complex and high cost, where Nafion for example incorporates perfluorovinyl ether groups with sulfonate groups onto a tetrafluoroethylene (PTFE) backbone.⁵⁴ There also is a gas diffusion layer as part of the multi-layer MEA, consisting of a type of carbon paper to allow additional channels for gas diffusion along the membrane. **Figure 11** shows a typical general schematic of a PEM fuel cell as well as a picture of a modern multi-cell fuel cell stack designed for automotive applications.

EV materials supply chains and future considerations

With the rapid growth in demand for advanced EV batteries, the nature and impacts of global battery supply chains are coming under increased scrutiny. There are major geographic imbalances in the locations of raw materials, the locations of battery and other component manufacturing locations, and the points of final vehicle assembly and use. For example, lithium may be mined in South America, minimally processed, and then shipped to China or Korea for further processing into EV batteries. These batteries may then be shipped, again as one example, to a vehicle assembly plant in Mexico, for delivery to North American markets. All of these steps involve transportation costs and emissions, and potential for supply chain interruptions. In response to these considerations, the US government has launched a strategic initiative around sourcing materials for lithium batteries with domestic supplies. New lithium mines based on rich soil deposits are beginning to start operations in Nevada to help support US production of lithium batteries.

Furthermore, key issues involve battery re-purposing (for stationary power) of EV batteries at “end of life” where typically significant (70–80%) power and capacity remains in the battery. EV batteries with some degree of refurbishment and re-configuration can have a “second life” in stationary applications until they are further degraded. This could help reduce and more carefully manage the up to 4 million metric tons of spent EV batteries that are projected through 2040 in one analysis.⁵⁶ Another analysis highlights the increased importance of closed-loop battery recycling over time with greater EV adoption, as well as the fact that

second life purposing of batteries offers fundamental materials use advantages, but somewhat delays the accumulation of volumes of batteries to recycle.⁵⁷

Ultimately, at end of life, EV batteries and other electrical and structural components will be carefully re-processed for recycling of materials economical to recover, and disposal of other materials. A battery processing industry is emerging around this resource, with the ability to produce similar quality materials (e.g., processed nickel) upon re-processing as virgin materials. However, one analysis finds that as of 2014, only 42% of the lithium battery waste stream was currently being recycled in the United States, including aluminum, cobalt, copper, nickel, and steel, where lithium and manganese were not yet being recycled at high rates.⁵⁶

Conclusions

In conclusion, EV technologies employ a suite of materials that are not traditionally used in the automotive industry. These include a variety of elements, metals, and composite materials that are used in EV batteries, motors, fuel cells, hydrogen storage systems, lightweight body structures, and electronics and control systems. Recycling of EV materials in the future will be critical to reducing demands of virgin materials, especially for strategic materials such as nickel, cobalt, lithium, platinum, and rare-earth materials such as neodymium, cerium, and dysprosium. Concerted industry efforts to reduce reliance on these strategic materials are likely to produce continued progress in the future, but with uncertainties related to the extent and timing of these improvements.

To some extent, use of these materials overlaps with developments with advanced conventional vehicles, especially with regard to lighter weight vehicle body materials. For combustion engine vehicles, lightweight construction has previously focused on the car body and the engine components, whereas EV material development is also important for the larger bodywork as well as the battery housing. The development of lightweight materials that can withstand high temperatures is now including properties such as shock resistance and thermal conductivity. The mechanisms and methods for material development are based on the same fundamentals, but manufacturing processes, such as additive manufacturing for functional graded materials, are constantly evolving.

Thus, EV technologies will surely continue to evolve rapidly in the coming years, suggesting shifts in materials and resources as these developments occur. Future battery, electric motor, fuel cell, and other technologies will continue to present challenges and opportunities for the automotive industry from a materials perspective, hopefully with a shift to the most environmentally benign and recyclable materials in the future. Considerations should include environmentally and socially responsible materials extraction and use, along with

the economic efficiency of EV materials supply chains as they expand in the future.

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References

1. M. Gallucci, *EVs Will Drive a Lithium Supply Crunch* (IEEE Spectrum, May 5 2021). <https://spectrum.ieee.org/evs-to-drive-a-lithium-supply-crunch>. Accessed 10 Aug 2021
2. H. Ambrose, A. Kendall, *J. Ind. Ecol.* (2019). <https://doi.org/10.1111/jiec.12949>
3. P. Greim, A.A. Solomon, C. Breyer, *Nat. Commun.* **11**, 4570 (2020). <https://doi.org/10.1038/s41467-020-18402-y>
4. T.G. Goonan, *Lithium Use in Batteries* (U.S. Geological Survey Circular 1371, 2012). <http://pubs.usgs.gov/circ/1371/>. Accessed 7 Jul 2021
5. E.A. Olivetti, G. Ceder, G.G. Gaustad, X. Fu, *Joule* **1**(2), 225 (2017). <https://doi.org/10.1016/j.joule.2017.08.019>
6. Y. Lyu, X. Wu, K. Wang, Z. Feng, T. Cheng, Y. Liu, M. Wang, R. Chen, L. Xu, J. Zhou, Y. Lu, B. Guo, *Adv. Energy Mater.* (2020). <https://doi.org/10.1002/aenm.202000982>
7. Z. Qi, G.M. Koenig, *Chem. Sel.* **1**(13), 3992 (2016). <https://doi.org/10.1002/slct.201600872>
8. G. Amatiucci, A. Du Pasquier, A. Blyr, T. Zheng, J.-M. Tarascon, *Electrochim. Acta* **45**(1), 255 (1999)
9. A. Purwanto, C.S. Yudha, U. Ubaidillah, H. Widiyandari, T. Ogi, H. Haerudin, *Mater. Res. Express* **5**, 122001 (2018)
10. S. He, S. Huang, S. Wang, I. Mizota, X. Liu, X. Hou, *Energy Fuels* **35**(2), 944 (2021). <https://doi.org/10.1021/acs.energyfuels.0c02948>
11. A. Li, A.C.Y. Yuen, W. Wang, I.M. De Cachinho Cordeiro, C. Wang, T.B.Y. Chen, J. Zhang, Q.N. Chan, G.H. Yeoh, *Molecules* **26**, 478 (2021). <https://doi.org/10.3390/molecules26020478>
12. W. Liguang, L. Jun, L. Guolong, L. Wenyan, T. Qiqi, S. Caihong, J. Huile, C. Guang, W. Shun, *Front. Mater.* **7**, 111 (2020). <https://doi.org/10.3389/fmats.2020.00111>
13. T.M. Gür, *MRS Bull.* **46**(12), (2021). <https://doi.org/10.1557/s43577-021-00242-w>
14. United States Geological Survey, *Rare Earth Elements Map of the Globe* (MR Data, 2021). <https://mrdata.usgs.gov/ree/map-us.html>. Accessed 8 Sept 2021
15. R. Powell, P.E. Krajewski, A.A. Luo, in *Materials, Design and Manufacturing for Lightweight Vehicles*, P.K. Mallick, Ed. (Woodhead Publishing, 2021) pp. 125–186, <https://doi.org/10.1016/B978-0-12-818712-8.00004-5>
16. W.J. Joost, P.E. Krajewski, *Scr. Mater.* **128**, 107 (2017). <https://doi.org/10.1016/j.scriptamat.2016.07.035>
17. T.T.T. Trang, J.H. Zhang, J.H. Kim, A. Zargar, J.H. Hwang, B.-C. Suh, N.J. Kim, *Nat. Commun.* **9**, 2522 (2018). <https://doi.org/10.1038/s41467-018-04981-4>
18. J. Wang, Z. Wu, S. Gao, R. Lu, D. Qin, W. Yang, F. Pan, *J. Magnes. Alloys* **3**(1), 79 (2015). <https://doi.org/10.1016/j.jma.2015.02.001>
19. Z. Gui, F. Wang, J. Zhang, D. Chen, Z. Kang, *J. Magnes. Alloys* (2021). <https://doi.org/10.1016/j.jma.2021.03.023>
20. L. Bolzoni, U. Joshi, R. Alain, D. Garetto, N. Hari Babu, *Mater. Sci. Eng. A* **723**, 70 (2018). <https://doi.org/10.1016/j.msea.2018.03.005>

21. K. Hono, C.L. Mendis, T.T. Sasaki, K. Oh-Ishi, *Scr. Mater.* **63**(7), 710 (2010). <https://doi.org/10.1016/j.scriptamat.2010.01.038>
22. V. Balaji, V.K. Bupesh Raja, K. Palanikumar, Ponshanmugakumar, N. Aditya, V. Rohit, *Mater. Today* **46**(9), 3769 (2021). <https://doi.org/10.1016/j.matpr.2021.02.017>
23. A.A. Luo, *JOM* **54**, 42 (2002). <https://doi.org/10.1007/BF02701073>
24. J.H. Jackson, P.D. Frost, A.C. Loonam, L.W. Eastwood, C.H. Lorig, *JOM* **1**, 149 (1949)
25. C. Li, Y. He, H. Huang, *J. Magnes. Alloys* **9**(2), 569 (2021). <https://doi.org/10.1016/j.jma.2020.02.022>
26. S. You, Y. Huang, K.U. Kainer, N. Hort, *J. Magnes. Alloys* **5**(3), 239 (2017). <https://doi.org/10.1016/j.jma.2017.09.001>
27. Q. Zhang, Q. Li, X. Jing, X. Zhang, *J. Rare Earths* **28**(1), 375 (2010). [https://doi.org/10.1016/S1002-0721\(10\)60336-5](https://doi.org/10.1016/S1002-0721(10)60336-5)
28. J. Wang, P. Song, S. Huang, F. Pan, *Mater. Lett.* **93**, 415 (2013). <https://doi.org/10.1016/j.matlet.2012.11.076>
29. K. Hantzsche, J. Bohlen, J. Wendt, K.U. Kainer, S.B. Yi, D. Letzig, *Scr. Mater.* **63**(7), 725 (2010). <https://doi.org/10.1016/j.scriptamat.2009.12.033>
30. T.W. Cain, J.P. Labukas, *npj Mater. Degrad.* **4**, 17 (2020). <https://doi.org/10.1038/s41529-020-0121-2>
31. R.S. Busk, D.L. Leman, J.J. Casey, *JOM* **2**, 945 (1950)
32. P.D. Frost, R.V. Whittenburg, J.G. Kura, L.W. Eastwood, *The Development of Magnesium-Lithium Base Alloys for Armor Plate, Report to Bureau of Aeronautics* (Contract NOa(s) 9526, Battelle Memorial Institute, Columbus, OH, 1950)
33. W.R.D. Jones, G.V. Hogg, *J. Inst. Met.* **85**, 255 (1956)
34. I.J. Polmear, *Light Alloys*, 4th ed. (Butterworth-Heinemann, Oxford, UK, 2005)
35. R.J. Jackson, P.D. Frost, *Properties and Current Applications of Magnesium-Lithium Alloys* (NASA SP-5068, Office of Technology Utilization Division, Washington, DC, 1967)
36. M.Y. Drits, Z.A. Sviderskaya, F.M. Yelkin, V.F. Trokhova, *Superlight Structural Alloys* (Nauka, Moscow, 1972)
37. W. Xu, N. Birbilis, G. Sha, Y. Wang, J.E. Daniels, Y. Xiao, M. Ferry, *Nat. Mater.* **14**, 1229 (2015)
38. P. Maier, N. Lauth, C.L. Mendis, M. Bechly, N. Hort, *JOM* **71**(4), 1426 (2019). <https://doi.org/10.1007/s11837-019-03359-1>
39. A. Buling, J. Zerrer, *Surf. Coat. Technol.* **369**, 142 (2019). <https://doi.org/10.1016/j.surfcoat.2019.04.025>
40. A.L. Rominiyi, K.M. Oluwasegun, J.O. Olawale, M.B. Shongwe, A.R. Adetunji, *Mater. Today* **38**(2), 1031 (2021). <https://doi.org/10.1016/j.matpr.2020.05.670>
41. M. Liu, Y. Guo, J. Wang, M. Yergin, *npj Mater. Degrad.* **2**, 24 (2018). <https://doi.org/10.1038/s41529-018-0045-2>
42. M. Hartmann, M. Roschitz, Z. Khalil, *Mater. Sci. Forum* **765**, 818 (2013). <https://doi.org/10.4028/www.scientific.net/msf.765.818>
43. R.N. Lumley, in *Metals and Surface Engineering, Fundamentals of Aluminium Metallurgy*, R.N. Lumley, Ed. (Woodhead Publishing, 2018), pp. 217–247. <https://doi.org/10.1016/B978-0-08-102063-0.00007-2>
44. G. Schuh, G. Bergweiler, F. Fiedler, M. Koltermann, *Procedia CIRP* **93**, 137 (2020). <https://doi.org/10.1016/j.procir.2020.04.038>
45. T. Furuta, in *Titanium for Consumer Applications Automobile Applications of Titanium*, F. Froes, M. Qian, M. Niinomi, Eds. (Elsevier, 2019), pp. 77–90. <https://doi.org/10.1016/B978-0-12-815820-3.00006-X>
46. M. Delogu, L. Zanchi, C.A. Dattilo, M. Pierini, *Mater. Today Commun.* **13**, 192 (2017). <https://doi.org/10.1016/j.mtcomm.2017.09.012>
47. M.K. Hagnell, S. Kumaraswamy, T. Nyman, M. Åkermo, *Heliyon* **6**, 3 (2020). <https://doi.org/10.1016/j.heliyon.2020.e03716>
48. D.-A. Türk, R. Kussmaul, M. Zogg, C. Klahn, A. Spierings, H. Könen, P. Ermanni, M. Meboldt, *J. Adv. Mater.* **3**, 1404 (2016). <https://doi.org/10.3929/ethz-a-010691526>
49. T. Gumpinger, H. Jonas, D. Krause, *Proc. ICED 09 Des. Methods Tools* **6**, (2009), pp. 201–210
50. T. Hofman, M. Steinbuch, R. van Druten, A. Serrarens, *World Electr. Veh. J.* **1**, 215 (2007). <https://doi.org/10.3390/wevj1010215>
51. H. Yim, K. Lee, *World Electr. Veh. J.* **7**, 426 (2015). <https://doi.org/10.3390/wevj7030426>
52. Y. Sun, M. Delucchi, J. Ogden, *Int. J. Hydrogen Energy* **36**(17), 11116 (2011). <https://doi.org/10.1016/j.ijhydene.2011.05.157>
53. L. Merlo, A. Ghielmi, V. Arcella, in *Encyclopedia of Electrochemical Power Sources* (Elsevier, 2009). <https://doi.org/10.1016/B978-0-44452745-5.00930-8>
54. A. Kusoglu, A.Z. Weber, *Chem. Rev.* **117**(3), 987 (2017). <https://doi.org/10.1021/acs.chemrev.6b00159>
55. N.A.H. Rosli, K.S. Loh, W.Y. Wong, R.M. Yunus, T.K. Lee, A. Ahmad, S.T. Chong, *Int. J. Mol. Sci.* **21**, 632 (2020). <https://doi.org/10.3390/ijms21020632>
56. K. Richa, C.W. Babbitt, G. Gaustad, X. Wang, *Resour. Conserv. Recycl.* **83**, 63 (2014). <https://doi.org/10.1016/j.resconrec.2013.11.008>
57. C. Xu, Q. Dai, L. Gaines, *Commun. Mater.* **1**, 99 (2020). <https://doi.org/10.1038/s43246-020-00095-x>

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