Materials and packaging solutions for energy storage systems used in electromobility

Abstract

Electromobility is emerging as a global alternative to transportation based on the internal combustion engine. Battery technology is largely responsible for the recent success of electric vehicles, from bicycles to passenger cars and buses. A sustained drop in lithium-ion battery costs and performance improvements are also pushing the limits of design. In this paper, we explore ways to maximize the value of packaging and cooling of lithium-ion energy storage systems (ESS) for different types of electric vehicles. We advocate the use of durable flame retardant polycarbonates for packaging components and the adoption of modular designs that can help capture value, allow multiple applications, and facilitate second-life use.

Introduction

A sustained drop in battery costs and performance improvements are fueling global innovation in electromobility. At the same time, adoption of stationary energy storage systems is surging, driven by the increased use of intermittent renewable energy sources including wind and solar, peak-power shaving applications, power modulation and emergency back-up energy storage. These changes are also pushing the limits of design. In particular, designers are looking for ways to maximize the value of lithium-ion energy storage systems.

In this paper, we examine these trends and focus on materials and packaging solutions for energy storage systems used in electromobility. Even though packaging represents a small fraction of the cost of any ESS, it is an essential component that enables functionality, safe operation and the ability to capture value over the product lifecycle.

In the next section, we identify different modes of electromobility and their corresponding market, configuration and performance requirements. We explore the concept of modularity as a step in the evolution of ESS as a product.

The section on safety and compliance addresses the need to consider existing and upcoming regulatory restrictions. This is relevant for designers who need to ensure safe operation of ESS, not only for mobile applications, but also for potential second-life use.

Based on this landscape of multiple applications and associated requirements, we propose material and design solutions for ESS. These concepts account for technical issues related to performance and cell behavior, including thermal management. Finally, we present overall lessons learned and conclusions.

Multi-modal electromobility

Electromobility is taking place around the world in a diversity of vehicles and markets. Table 1 shows the main types of electric vehicles and some characteristics of their markets.

Electric Vehicle	Market Highlights
Light EVs – LEVs  Electric bicycles, pedelecs, scooters	• No public incentives • 30+million LEVs in China • Robust pedelec growth in the EU region
Plug-in hybrid EVs – PHEVs  Internal combustion/electric powertrain	• Versatile • Limited electric range • Avoid "range anxiety" • Regional penetration varies
Battery EVs – BEVs  Cars and trucks with 100 % electric powertrain	• Urban vehicles • eco-EVs in China • High performance EVs • New models with increased range
Heavy duty EVs  Electric buses, trucks and utility vehicles	• e-buses in megacities • New utility e-vehicles • Rapid charging may require liquid cooled batteries

Table 1: Electric vehicle type and market highlights

Light EVs – LEVs

Light electric vehicles are experiencing unprecedented growth in many parts of Asia and Europe [1, 2]. Along with public transportation, LEVs provide one of the most efficient and sustainable means of urban transport at the lowest operational cost and environmental impact [3]. As the range of LEVs is continuously increasing, they are suitable for leisure, inner city passenger transport and delivery of goods. They also provide affordable mobility options for many social groups, including some in the developing world.

A wide diversity of LEVs now demand energy storage systems which are versatile and robust, mimicking the requirements of battery packs used for consumer electronics. These requirements include toughness, high modulus, dimensional stability, flame retardance and good flow for thin wall injection molding. Capacity for energy storage systems for bicycles, pedelecs and scooters range from 0.2 to 5 kWh and are comprised of a collection of cylindrical or prismatic cells housed in a self-contained enclosure with an integrated battery management system.

These packs may be swapped or charged in place and therefore require rather tough (impact resistant) and durable housings. These ESS are generally air-cooled and rely on conduction to dissipate heat, which is usually highest during charge and discharge cycles. For this reason, the wall thickness of thermoplastic enclosures should be kept to a minimum. The geometric complexity of the ESS assembly and the need for precise cell placement demands the use of high-flow injection molded plastics that are also flame retardant. These and other considerations are taken into account in the design concepts shown below.

Plug-in Hybrid EVs – PHEVs

Plug-in hybrids represent a rising class of electric vehicles being introduced by automotive OEMs globally. They provide a compromise between total powertrain electrification and fossil-fuel powered vehicles, reducing the so-called "range anxiety" of some consumer groups. As battery costs continue to decline, the capacity of ESS for PHEVs is increasing alongside their pure electric range. The flagship representative of this class is the Chevy Volt, which provides 53 miles (85 km) of electric range in its 2015 model. Numerous OEMs are launching PHEVs in the years ahead, as CAFE and greenhouse gas reduction mandates are taking effect in the US and the rest of the world.

Energy storage systems for PHEVs usually range from 4 to 19 kWh, providing an electric range between 10 and 50 miles (16 to 80 km), as required by most commuters. Such systems are comprised of anywhere from 50 to 500 cylindrical, prismatic or pouch cells, cooled by air or fluid. The size of the entire system may reach up to 440 lbs (200 kg) and packaging may contribute from 0.8 to 1.0 kg per kWh.

Externally, current designs appear monolithic although internally they are usually divided into functional modules of similar size. Enclosures, frames and trays are used to hold and secure cells and other components in place. Packaging may also provide a conduit for cooling media and electrical insulation. The entire ESS is often enclosed in a metal or composite cover that provides protection against water intrusion and impact while integrating the battery and thermal management systems.

Battery EVs – BEVs

Battery electric vehicles represent a new class of passenger vehicle capable of disrupting the global automotive market. Despite their perceived range limitation and dependence on a charging infrastructure, BEVs continue to make inroads with an enthusiastic base of early adopters worldwide. Notwithstanding their high initial cost, BEVs are attractive due the simplicity of their design, zero-carbon emissions, low operational cost and minimum maintenance requirements.

Tesla Motors has been largely responsible for changing perceptions of BEVs worldwide. Automotive analysts consistently rank Tesla's Model S as a top vehicle in performance, quality and reliability. This vehicle also features the largest ESS of any passenger car: 90 kWh, which allows an official EPA (US) range of 270 miles (400 km). This system features a set of fluid-cooled modules composed of high-performance 18650-format cells.

Nissan takes a different approach toward the design of its 24kWh ESS for its bestselling BEV, the Leaf. This system is composed of 48 lithium-ion modules. Each module features four pouch cells enclosed in a prismatic aluminum can. The entire assembly is further housed in a sealed steel enclosure, which sits underneath the passenger seats and helps increase the car's structural rigidity.

Analysts agree the next battleground for the industry is a mid $30,000; 200 miles range BEV [4]. The contenders include Tesla Model 3, the Chevy Bolt and new vehicles to be announced by Nissan, Ford and Audi. BEV cost and performance is largely determined by their energy storage system. And although most of the focus is directed to battery cells, automotive and battery OEMs are finding new uses to both new and used battery modules in stationary applications. This creates an additional financial incentive to re-think ESS design, an idea we further explore in our section on modularity below.

Heavy duty EVs

Electromobility is also advancing in large, heavy-duty and utility vehicles including trucks, buses and forklifts, among others. Electric powertrains offer simple, easy-to-maintain transportation services at low operational costs. These solutions are particularly advantageous in applications where repeated and predictable use is required. This is the case for electric buses, where service routes and therefore charging cycles are clearly defined.

For fleet managers looking at ROI over several years of operation, commercial vehicles with electric powertrains are becoming increasingly attractive. In megacities around the world, the opportunity to reduce pollution is also favoring electrification.

ESS for this class of vehicles may be as large as 350 kWh and composed of modules designed to be swapped by automated equipment or rapidly charged during stops or breaks. In either case, packaging plays a critical role to ensure safe and quick handling and electrical connectivity.

Fluid or air-cooled systems are required during rapid charge and discharge cycles. In addition, vibration and structural integrity may be among the top concerns for the ESS in this vehicle type. Electrified retrofits are also emerging as an alternative to high fuel and maintenance costs of heavy duty trucks as demonstrated by the company Wrightspeed.

Modularity and battery lifecycle

In these early days of the electrification of transport, vehicle architecture is still rather integrated as a way to guarantee that performance is in line with user expectations. In particular, drivetrain components are adjusted toward that goal. The Tesla Model S is a good example of integrated vehicle architecture, carefully tuned to produce a high-performance vehicle, including a proprietary fast-charging interface.

This principle is explained by Christensen [5, 6] who argues that in the early stages of products, integrated architectures win over modular architectures because they come closest to meeting user requirements. Over time, as customer demands are satisfied, modular architectures which rely on standard interfaces are able to rapidly develop, change and refine components independently. This shortens the development cycle increasing flexibility, versatility and enabling the emergence of product development platforms.

From our point of view, energy storage systems will soon evolve toward modularity as part of natural cycle of electric vehicle and stationary energy storage systems. Battery modules with standard interfaces may be used as building blocks to satisfy the power and energy requirements of different types of electric vehicles, as described above.

Fig. 1 shows a universal battery module introduced by Constin GmbH [7]. This module called GreenPack is designed to be used as a building block of scalable ESS in mobile and stationary applications. A similar concept is being proposed by EnergyTube Holding GmbH with a cylindrical format [8]. VDMA, a German trade association of machine manufacturers, is also forming a consortium to develop new electric-driven products around a universal and modular battery design and communications protocol [9].



Fig. 1: GreenPack universal battery module

Currently, ESS for electric passenger vehicles tends to be over-engineered and may be able to retain 70 % of their capacity at the end of their vehicular life. This condition creates a strong argument for re-purposing former EV ESS into other applications.

Several companies and research labs have already implemented pilot programs that prove the feasibility and economics of this business model [10]. In this field, Spiers New Technologies is emerging as a leader, assessing and qualifying used EV cells and modules and repurposing them into new products. Some applications for former EV ESS modules include renewable energy storage, power-peak shaving, energy buffers for rapid EV charging and emergency back-up systems.

Repurposing modules also improves the economics of EVs, facilitates upgrades and creates new sources of revenue along the value chain. As improvements in battery technology outpace the automotive development cycle, OEMs may be able to offer consumers regular upgrades using the same glider. In addition, new research shows that battery degradation is below initial predictions [11], resulting in a longer-than-expected lifespan, further strengthening the case for modularity, repurposing and capturing residual value.

Modularity will not only enable a new class of electric products and applications, it will also reduce refurbishing costs, enable new business models and facilitate safe end-of-life disposal and recycling.

Safety and compliance

Packaging plays a critical role in ensuring the safe and reliable operation of energy storage systems. Various global and national Standard Development Organizations (SDOs) are creating standards, codes and regulations that enable the safe use of ESS [12, 13]. Fortunately, many of these organizations are harmonizing their efforts, avoiding duplicate work and accelerating the adoption of electric vehicles worldwide. The challenges listed by the ANSI EVSP Standardization Roadmap for Electric Vehicles capture the design goals of any given ESS. These challenges are safety, affordability, performance and environmental impact.

Compliance ensures that the ESS satisfies minimum safety requirements. Testing is used to assess the performance of cells, modules and packs. Testing conditions include battery abuse, transportation, handling, storage, recycling, crash, intrusion of components in the occupant compartment and electric shock. New standards are also being developed for secondary battery use and recycling.

Many of these requirements are not new to designers. Similar challenges have been successfully addressed with affordable and effective solutions by designers of automotive and electronic products. For example, flame-retardant, impact-resistant enclosures that house lithium-ion cells have been successfully designed for electronic devices such as laptops over the last two decades.

Although ESS packaging does not directly determine cell performance in terms of energy and power, properly designed frames and enclosures ensure efficient use of space, protection against damage and adequate thermal management. All of these factors ultimately affect power and energy density, safety and lifecycle.

In the next section, we explore cell packaging and cooling solutions compliant with international codes and standards and adapted for unique or multiple uses, as needed.

Materials, design, thermal management

Designing battery enclosures, frames or trays depends on many factors. Cell format and available packaging space are among the top concerns. However, we recognize that safety, compliance, performance and affordability are also major drivers. As EVs improve, we expect to see more advanced designs that that not only account for the immediate needs of a particular EV, but also allow for modularity, interoperability, second life uses and recycling.

The concepts we present here are just illustrative examples of solutions that take into account many of the factors mentioned above. The actual performance and design depends on the requirements of the OEM and should be validated and verified via testing by the manufacturer. Our design team at Covestro would be happy to assist in the development of these solutions.

Fig. 2 shows a typical design of an ESS for a light electric vehicle, such as an e-bike, pedelec or scooter. Typically they include an integrated electronic battery management system and external connectors for in-situ charging or swapping. Internally, the enclosure provides support and precise cell-placement with sub-millimeter features requiring precision injection molding. Externally, the enclosure provides mechanical interfacing, and protection against impact, dust and intrusion. In addition, this enclosure should be aesthetically pleasing, ergonomic and provide brand-identification. To comply with UL 2271 the enclosure should be flame-retardant V-2 UL 94 rated.

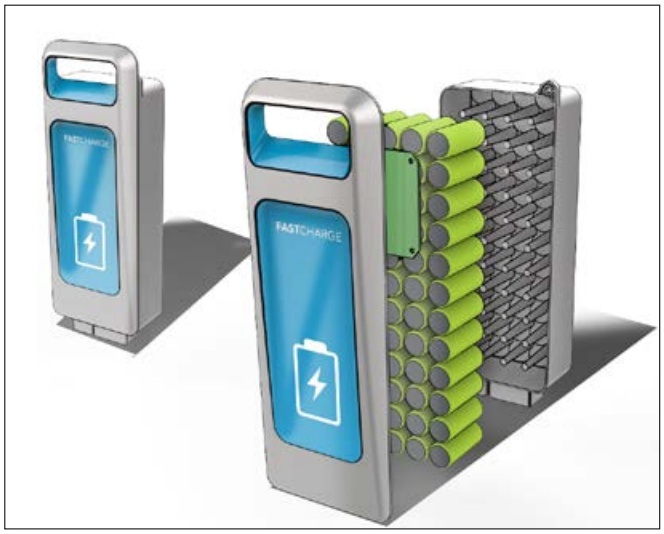


Fig. 2: Design concept: LEV ESS

For such cell holders or enclosures, we recommend Covestro's Makrolon® 1899 polycarbonate or PC/ABS Bayblend® FR3040. Materials like these have a long track record in lithium-ion battery packs with proven performance in IT, consumer electronics and medical devices.

PHEVs and EVs feature much larger energy storage systems. They are comprised of modules housed in large metal or composite enclosures that centralize the battery management and thermal management systems. Internal modules are still composed of trays or frames that hold cells in place providing dimensional stability and safe access to cooling media as needed. Depending on the OEM preference, the cell format could be cylindrical, prismatic or pouch (Figures 3, 4 and 5). These concepts may also be applicable to 48V mild hybrids.

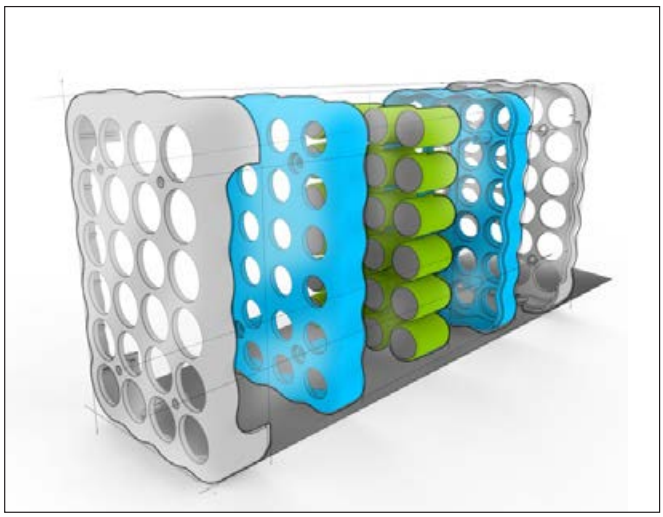


Fig. 3: Design concept: air-cooled ESS

For cylindrical cells, the use of injection molded thermoplastics trays is necessary. This solution guarantees the proper positioning and cooling given the cell geometry. Because cylindrical cells act as pressure vessels, designers are not concerned with swelling during charge and discharge cycles. However, delivering cooling media to critical areas becomes a challenge.

Fig. 4 shows one such concept made entirely of plastics. This concept eliminates the need to use separate conductive metal conduits, positioning cooling channels directly on the holding frame. The result is integrated functionality with a reduced number of components, using less space at a lower cost. The sealing between the frame with cooling channels and the lid may be achieved by overmolding a self-adhesive liquid silicone.

Thermal simulations and tests conducted by our engineering team shows that it is possible to achieve cooling performance targets despite the lower conductivity of thermoplastics - by choosing high-flow materials which allow thin walls to be molded. If necessary, our team would recommend a thermal interface material to ensure direct contact between the cell and frame walls.

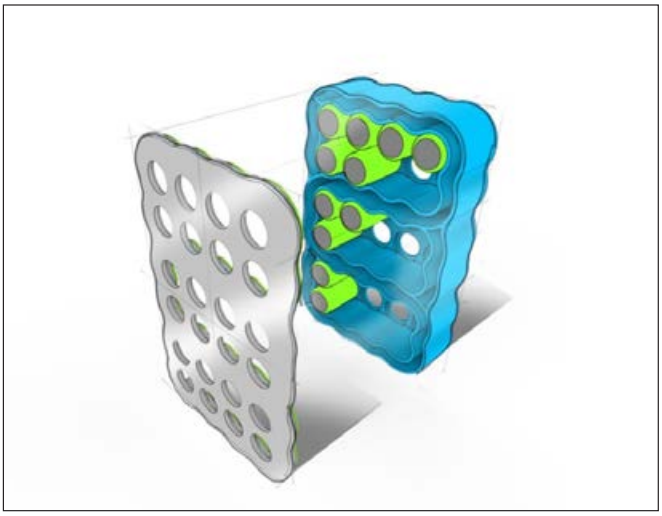


Fig. 4: Design concept: liquid-cooled cylindrical cell ESS

Similar solutions can also be achieved with pouch cells, as shown in Fig. 5. In this concept, the cooling channels are molded into the thermoplastic and an aluminum sheet is bonded with a self-adhesive silicone. In this design we build the complexity of the cooling channel into the injection molded part without any extra cost.

Due to their geometry, pouch cells are easy to fit into tight spaces, but packaging designs must also account for swelling during charge and discharge cycles. Frames must satisfy the need for precision molding with permanent water-glycol resistance, for which we recommend Covestro's new Bayblend® TP4065, a trial product with limited commercial availability. This material is also flame retardant, has excellent adhesion to self-adhesive silicone and overall good chemical and impact resistance.

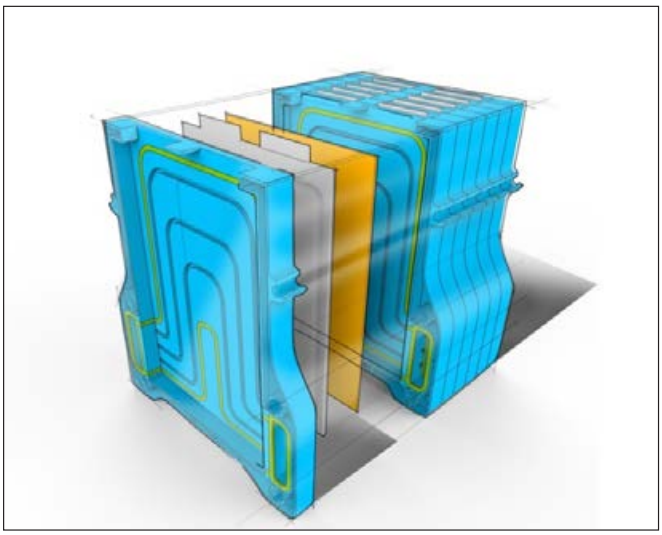


Fig. 5: Design concept: liquid-cooled pouch cell ESS

Fig. 6 shows a concept for an air-cooled prismatic cell package, as may be used in heavy-duty electric vehicles, such as e-buses and trucks. Our team has successfully implemented similar solutions for vehicles requiring long-term vibration tests. For such designs, we recommend a flame-retardant PC/ABS blend such as Covestro's Bayblend® FR3010.

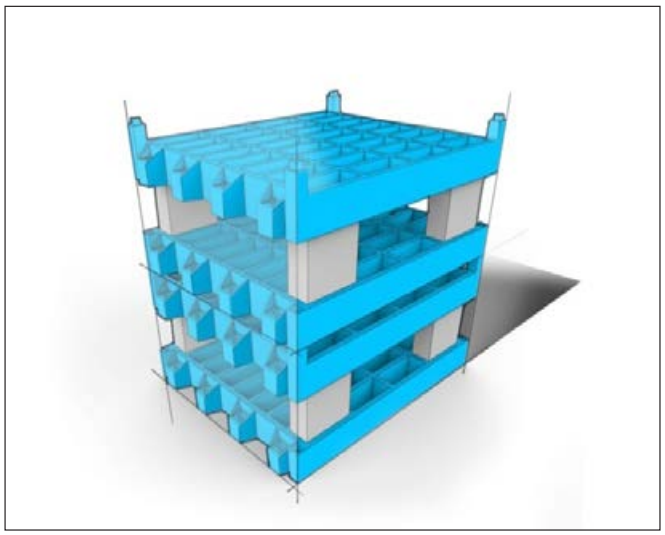


Fig. 6. Design concept: air-cooled prismatic cell ESS

For lithium-ion cell packaging we recommend the use of flame retardant polycarbonates, as they have shown to provide an additional level of safety against fire spread initiated by a short-circuit or an external ignition source. Flame retardant materials may help lower the risk otherwise catastrophic incidents that could result in loss of property and life.

Although vehicle performance requirements may limit ESS packaging design freedom, it is clear that electromobility is not just a replacement of conventional transportation. Instead, it is opening new ways to create and capture value in different classes of vehicles, devices and stationary applications. OEMs who understand this first will differentiate themselves and create a unique pull for their products.

Conclusions

Packaging used in the ESS of electric vehicles serves multiple functions including electrical connection and insulation, thermal management, mechanical interfacing, as well as flame retardance and impact resistance. Materials and design choices can influence packaging and ultimately the lifecycle of the ESS and its components.

With new products and design support, Covestro collaborates with ESS suppliers and their customers to provide advanced materials that offer new and diverse solutions to the emerging electromobility industry.

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