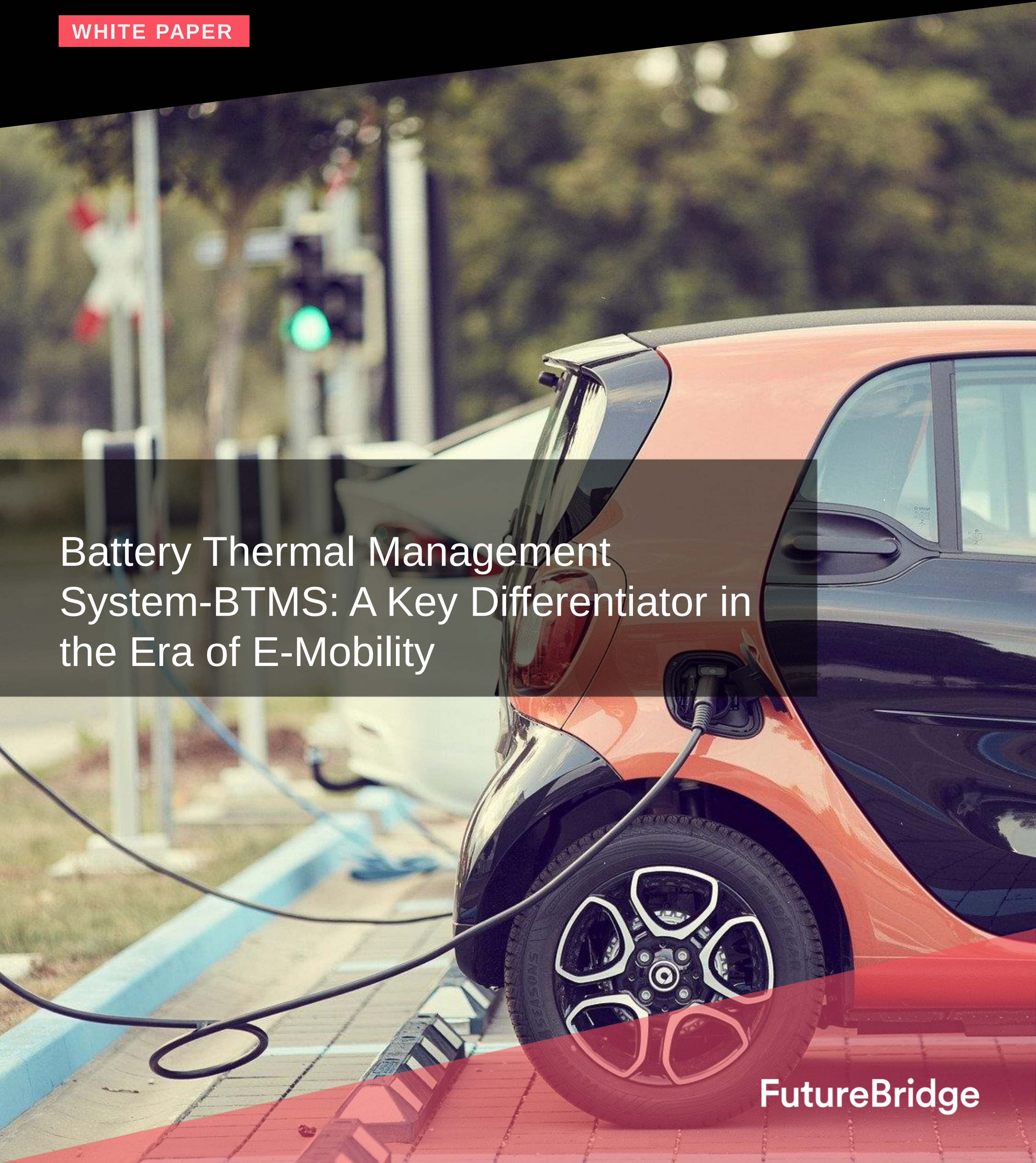
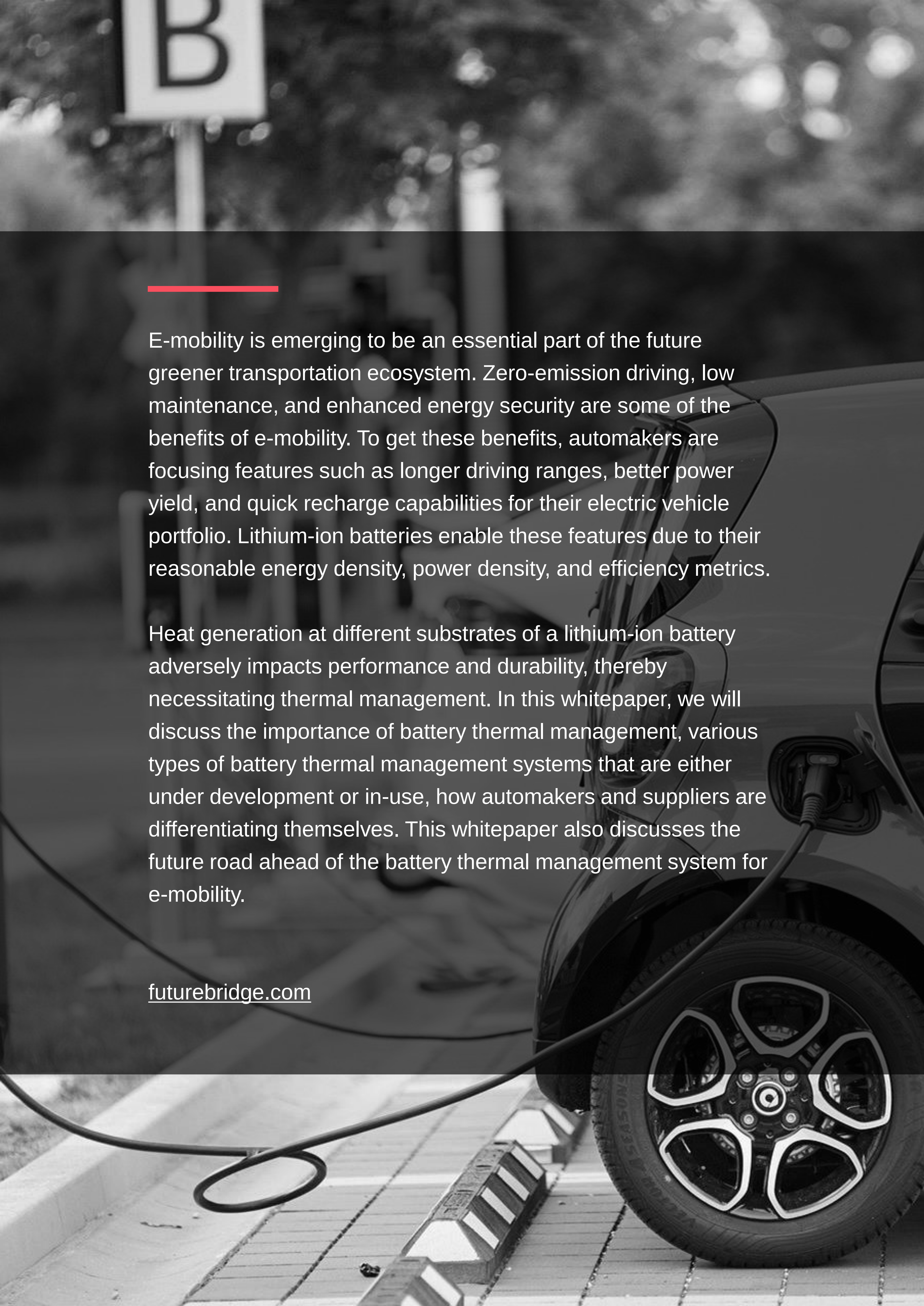
WHITE PAPER



Battery Thermal Management System-BTMS: A Key Differentiator in the Era of E-Mobility

FutureBridge



E-mobility is emerging to be an essential part of the future greener transportation ecosystem. Zero-emission driving, low maintenance, and enhanced energy security are some of the benefits of e-mobility. To get these benefits, automakers are focusing features such as longer driving ranges, better power yield, and quick recharge capabilities for their electric vehicle portfolio. Lithium-ion batteries enable these features due to their reasonable energy density, power density, and efficiency metrics.

Heat generation at different substrates of a lithium-ion battery adversely impacts performance and durability, thereby necessitating thermal management. In this whitepaper, we will discuss the importance of battery thermal management, various types of battery thermal management systems that are either under development or in-use, how automakers and suppliers are differentiating themselves. This whitepaper also discusses the future road ahead of the battery thermal management system for e-mobility.

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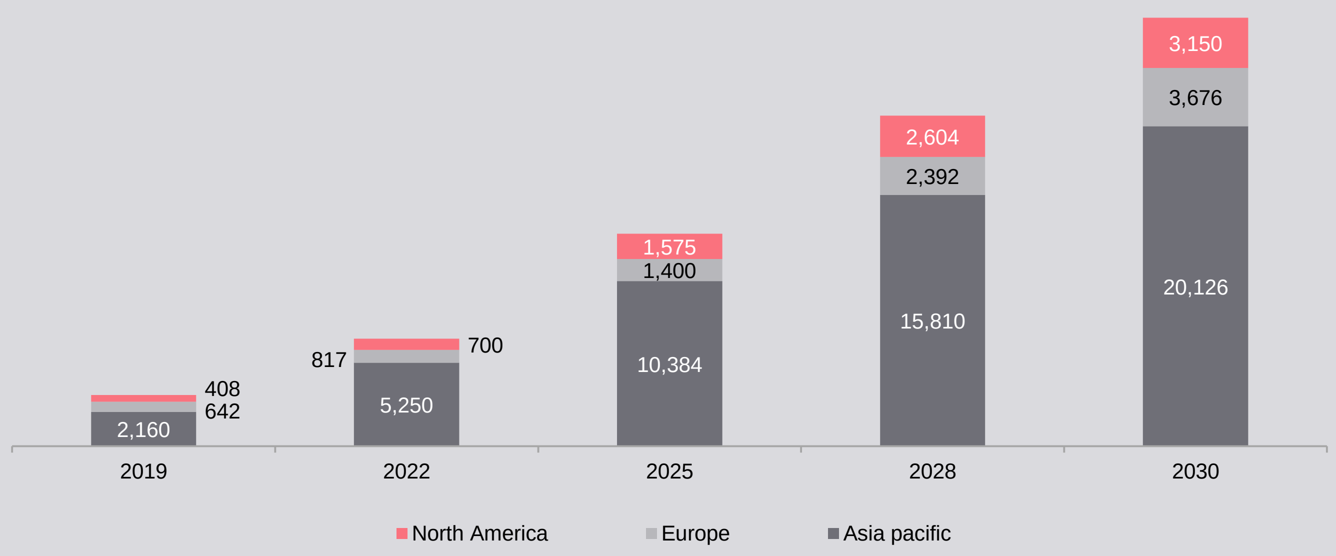
Baseline factor: Rise of Electric Vehicles

In the near future, electric vehicles are likely to grow after rapid development in the past decade. Automakers have started offering electric vehicles, starting from hybrid to full electric as a response to the growing environmental concerns arising from growing vehicle emissions.

Also, it has become essential for automakers to focus on features such as extended range, better power yield, and quick recharge capabilities for an electric vehicle. In all these features, the battery system of an electric vehicle plays an important role.

EXHIBIT 1: Electric vehicles sales by region (in thousands), 2019-2030



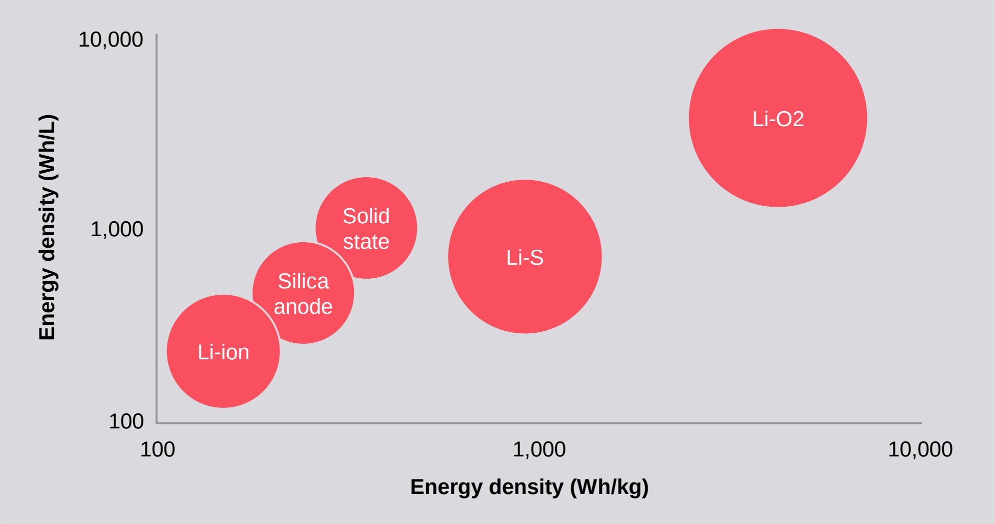
Source: FutureBridge Analysis and Insights

The battery technologies that have been prevalent in the electric vehicle industry have progressed from low energy density, i.e., lead-acid, nickel-cadmium, nickel-zinc, and nickel-metal hydride battery, to high energy density like the lithium-ion battery.

The emergence and widespread use of lithium-ion batteries have promoted the rapid development of electric vehicles to a great extent due to its excellent properties, such as high energy density, low self-charging, and low maintenance.

However, by increasing battery density, excess heat generation is another significant consequence that can lead to reduced battery performance. Therefore, various automakers and suppliers have gained interest in battery thermal management for electric vehicles.

EXHIBIT 2: Energy density by volume and weight



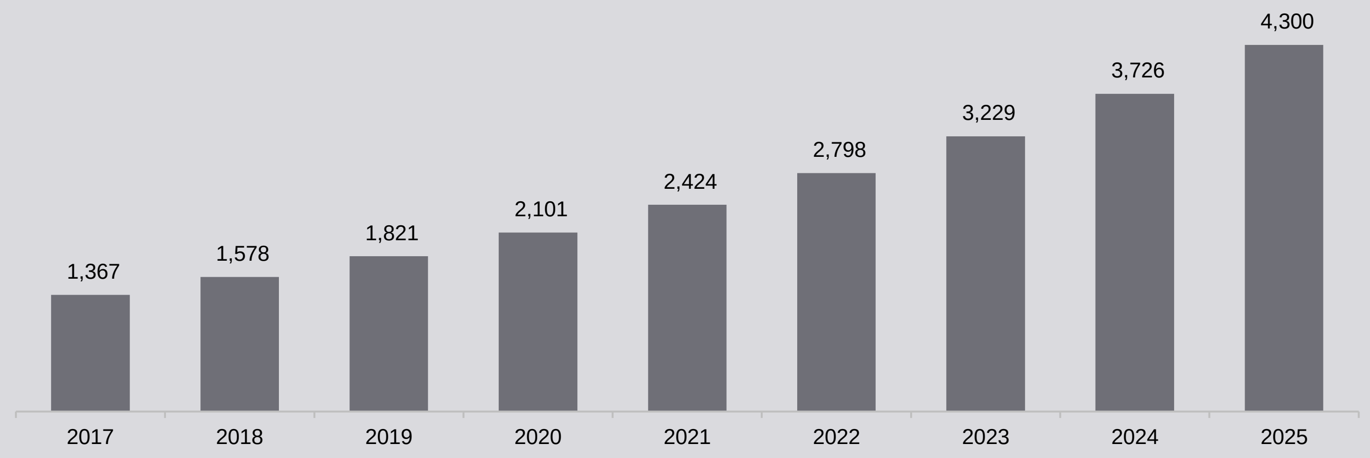
Growing Market of Battery Thermal Management Systems

Until the introduction of electric vehicles, the thermal management solutions in the vehicle were focused on engine cooling, waste heat recovery, fuel economy, and protection of components, auxiliary equipment, and the transmission.

Electric vehicles have changed the core tasks required. Controlling the temperature in the traction battery and cooling the power electronics and electric motor, integrating these different cooling systems and the efficient climate control in the vehicle interior, while also saving energy is now the main focus. Since electrically powered vehicles cannot utilize conventional methods as in combustion engines, this led to a challenge in developing new solutions from both thermal management and energy point of view.

The overall thermal management system market is estimated to grow at a very high CAGR, whereas, automotive battery thermal management system market is expected to grow at a CAGR of 15.04% during the forecast period - from USD 1.57 Billion in 2018 to a projected market size of USD 4.3 Billion by 2025.

EXHIBIT 3: Automotive Battery Thermal Management System Market, 2017-2025 (in USD millions)



Source: FutureBridge Analysis and Insights

Ecosystem

Thermal management is provided both by OEMs and suppliers, with OEMs handling the system integration and suppliers predominantly supplying subsystem components, e.g., pumps and valves.

EXHIBIT 4: Ecosystem of Automotive Battery Thermal Management Systems

Source: FutureBridge Analysis and Insights

Success factors for suppliers

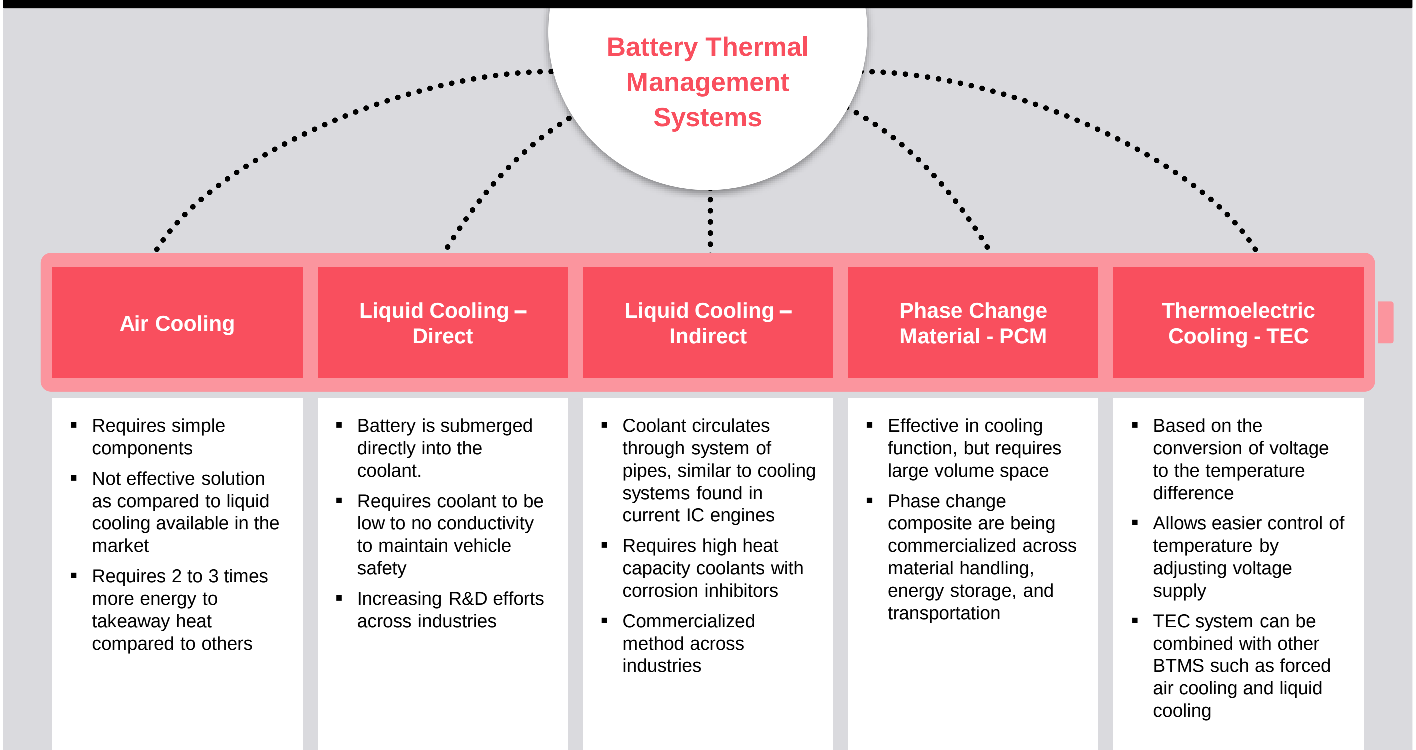
Since thermal management is becoming more sophisticated and differentiating in HEVs (the combination of two thermal management cycles) and BEVs (key influencer of efficiency, range, and battery lifetime), superior system understanding is key to the success for suppliers.

Specifically, suppliers with the ability to transfer knowledge from classical thermal management systems to the more complex hybrid thermal management systems will have a significant advantage. A comprehensive system understanding of thermal management for ICEs and EVs can lead to superior robustness and coolant flow control, thus improving vehicle range.

Types of BTMS

Advancements in batteries allow them to deliver more power and require less frequent charges, especially for electric vehicles. Battery safety is one of the significant challenges that can be addressed by designing an effective thermal management system in the following ways:

EXHIBIT 5: Types of Battery Thermal Management Systems



Source: FutureBridge Analysis

Air Cooling

Air cooling is an easy method to transfer heat away from the battery pack, wherein the air runs over the surface and will carry away the heat emitted by the pack. This method is based on the principle of convection. In the earlier versions of Nissan Leaf, air cooling was used. Generally, during driving, there is some air cooling on the battery positioned on the underside of the vehicle due to airflow, however, while charging, the vehicle should be stationary, and heat transfer has to be reduced.

The air cooling system is sensitive to ambient temperature, battery component material, the weight of the battery pack, and airflow rate, which makes this method less preferable by automakers for new high-performance applications. Automakers, such as Tesla, insist that liquid cooling is the safest method.

Liquid cooling systems have a division between direct and indirect, either the cells are submerged in the liquid or if the liquid is pumped through pipes.

Direct Liquid Cooling

The direct liquid cooling system consists of battery cells being immersed in the coolant liquid that results in the highest efficiency of all the methods. This direct contact among the coolant and the battery pack also results in the least thermal resistance path from components to the coolant. The coolant is electrically non-conductive; otherwise, that can cause shorting of the cells and lead to breakdowns.

The thermal conductivity of this method is less compared to coolants, such as water and glycol. Therefore, the amount of coolant in the battery pack is increased. Based on all these essential factors, it can be said that a direct liquid cooling system is bulky. Also, this method increases the mass of the battery pack that will reduce the energy density of the battery pack.

Currently, this method is in the research and development stage, with no automakers on the market using this system.

Indirect Liquid Cooling

The indirect liquid cooling method is used in ICE cooling systems wherein the coolant is passed through a series of metal pipes. However, in electric vehicles, this method is deployed differently. In this method, water and glycol coolant is distributed among battery packs and various other components and vehicle power electronics. The method is assumed to similar to air cooling, wherein the coolant is used for cooling instead of air. The structure of this system is designed to have maximum temperature uniformity. Also, this system is dependent on the shape of the battery pack and will look different for each automaker.

In addition to temperature uniformity, this system has advantages like compact structure and ease of arrangement. On the other hand, indirect liquid cooling systems have their safety issues related to the leaking of coolant, wherein glycol can be environmentally fatal if not handled properly. Tesla is using this system in the Model S and Model 3 battery packs. Similarly, other automakers such as Jaguar and BMW have deployed this system for their car portfolio.

Thermoelectric Cooling-TCM

In the recent years, Thermoelectric Cooling or TCM has drawn attention in the industry. In this system, the coolers are based on the conversion of voltage to the temperature, which is also known as Peltier –Seebeck effect, together coupled with the Thompson effect. This system also comes with benefits of being noiseless, stable, and enabling to have control of temperature by regulating the voltage supply.

As per one of the scientific studies, this system had the cold sides of coolers in contact with the heat sink, and the maximum temperature was kept below 55°C. For cooling the battery pack and cabin, cold air was blown into the battery system, and later, a heat sink-fan set for both the cold side cooling and the hot side heat dissipation was incorporated.

Besides, thermoelectric cooling can be used in combination with other battery thermal management systems, such as forced air cooling and liquid cooling.

Phase Change Material-PCM

To meet various challenges set by the above discussed thermal management systems, automakers saw potential in using a combination of these systems. Similar to direct liquid cooling, in the PCM system, the liquid is poured inside the battery pack, and the material solidifies below a working temperature range based on the variant selected. After the assembly solidifies, if a part of the battery pack solidifies, the PCM around will change its phase at a predetermined temperature.

PCM system can meet the cooling requirements of the battery pack; however, the volume change that occurs during a phase change restricts its application. On the downside, PCM can only absorb heat generated, not transfer it away, which means it won’t be able to reduce the overall temperature as well as other systems.

EXHIBIT 6: Battery cooling system of various automakers

Model	Launch year	Types of battery cooling	
		Air	Liquid
Chevrolet Spark	2014		✓
Chevrolet Bolt	2017		✓
Tesla Model S	2013		✓
Tesla Model 3	2017		✓
VW e-up	2013	✓	
VW e-golf	2015	✓	
VW e-golf	2019	✓	
Nissan LEAF	2017	✓	
Nissan LEAF	2011	✓	
Audi e-tron	2019		✓
Jaguar I-PACE	2018		✓
Kia Niro	2017		✓
BMW i3	2014		✓

Source: FutureBridge analysis

OEM’s and Supplier’s initiatives

At present, automakers such as Tesla, Audi, and BMW have deployed an indirect liquid cooling system for their offered electric vehicles in order to maintain the battery heat levels.

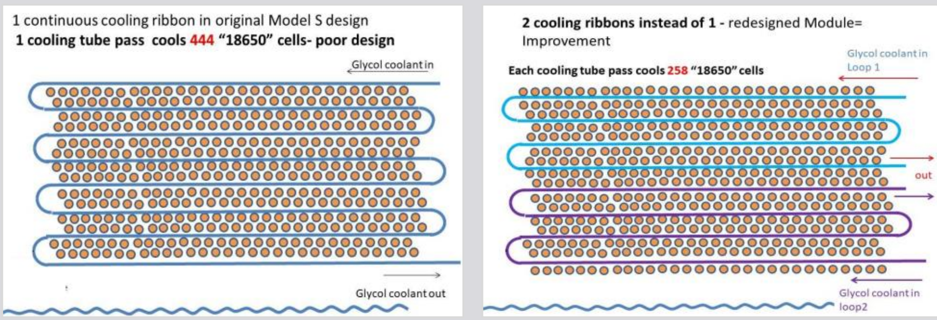
EXHIBIT 7: Automakers, suppliers and research group initiatives towards Battery Thermal Management Systems

Automakers	TESLA	▪ Tesla relays on liquid glycol cooling for its car offerings ▪ Tesla Model 3 has a new battery new design that has improved cooling than Model S ▪ The cooling system has machine assembled tubing, also called as bandolero, has two ribbon-shaped cooling tubes, as compared to one in the gen 1 module
	AUDI	▪ Audi also uses liquid cooling wherein 5.8 gallons of coolant circulating through a 40 meter tube in combination with a typical heat pump in its fully electrical model e-tron ▪ The system ensures that the battery is kept within its optimal efficiency range of 25 to 35 degrees Celsius
Suppliers	XING	▪ XING Mobility introduced immersion cooled modular battery pack system in 2019, that will enable automakers to install and connect power in a matter of hours.
	DUPONT	▪ In 2019, DuPont introduced a series of materials for thermal management systems during Auto Shanghai 2019 ▪ BETASEAL TC, Thermal-Conductive Interface Material used in battery cells for maintaining the temperature uniformly ▪ BETAFORCE, Thermal-Conductive Adhesive that can also serves the function of vibration inhibitions, variations and tensions caused by thermal differences among layers that are critical for the battery durability
Research group	i-CoBat project RICARDO, WMG, M&I MATERIALS	▪ i-CoBat project, under UK government’s Faraday Battery Challenge, aims to develop new battery cooling system using immersion fluids. ▪ The project consists of naming, M&I Materials, Warwick Manufacturing Group (WMG) and Ricardo plc. ▪ M&I Materials has come up with a biodegradable cooling fluid named MIVOLT aimed to optimise battery cooling system

Source: FutureBridge analysis

The Tesla Model 3 that has a new battery design that consists of improved cooling over Model S. The cooling system has machine assembled tubing, also called bandolero, has two ribbon-shaped cooling tubes, as compared to one in the gen 1 module.

EXHIBIT 8: Battery cooling system of Tesla Model S and Model 3



Audi uses 5.8 gallons of coolant circulating through a 40-meter tube in combination with a typical heat pump in its fully electrical model e-tron. The system consists of four circuits that can cool the electric motors, including their rotors, the power electronics, and the charger. The system also ensures that the battery is kept within its optimal efficiency range of 25 to 35 degrees Celsius in all situations, from a cold start in winter to fast highway driving on hot summer days.

On the supplier front, Taiwan-based XING Mobility introduced an immersion-cooled modular battery pack system at The 2019 Battery Show in Stuttgart, Germany. The company will launch this thermal system in parallel to complement its advanced, integrated components and fully compatible powertrain solutions. The company believes that this all-in-one, plug-and-play system will enable automakers to install and connect power in a matter of hours, without having any prior experience of electric vehicle assembly systems.

DuPont Transportation & Advanced Polymers (T&AP), a business unit of DowDuPont Specialty Products Division, introduced a series of materials for thermal management systems during Auto Shanghai 2019. Few of them are BETASEAL TC, Thermal-Conductive Interface Material used in battery cells for maintaining the temperature uniformly. Subjected to the durability of the battery pack, the company introduced BETAFORCE, Thermal-Conductive Adhesive, which can also serve the function of vibration inhibitions, variations, and tensions caused by thermal differences among layers that are critical for the battery durability.

In Europe, under the UK government's Faraday Battery Challenge, the i-CoBat project aims to develop a new battery cooling system using immersion fluids. The project is led by a special material providing company, M&I Materials that has come up with a biodegradable cooling fluid named MIVOLT. In this project, Warwick Manufacturing Group (WMG), the manufacturing research arm of the University of Warwick, and engineering consultancy Ricardo plc. are partnering with M&I Materials to optimize the battery cooling system for a longer-lasting, safer battery product.

The Road Ahead – Future of BTMS

Technology trends shaping the next generation of BTMS

Thermal management using 48V: The availability of 48V power supply will lead to the deployment of more electric-powered thermal management components having more efficiency, better performance, and less energy-consuming than conventional mechanical or 12V-enabled parts. Also, quieter vehicles from electrification raise the requirements for mechanical components (e.g., pumps, ventilators) to also be quieter, which is achieved either via increased noise insulation or via the optimized design of the complete thermal management system.

Higher thermal resistance: The transition of semiconductors in the power electronics system from Silicon Oxide (SiO) to Silicon Carbide (SiC) will result in less heat loss from power electronics and thus reduced cooling requirements. Also, this will allow for an increased current density, which will further enable faster charging.

Lithium-ion battery improvements: Various initiatives are being carried out to improve the performance of the battery system. Researchers at Stanford University have developed a battery design with a flexible transparent screen that can store energy, whereas, in Japan, Toyota, a leading automaker, has developed a transparent lithium-ion battery that charges using sunlight to using renewable energy. The automaker is planning to integrate this system into the car window. Furthermore, nanotechnology potentially offers to create enhanced lithium-ion batteries that offer better durability, safety, and improved performance at an affordable cost.

These new technologies will enhance the performance of the lithium-ion battery system to enable new application areas and also harness the need for the new battery thermal management system.

Which type of BTMS is most viable?

Almost every automaker has its method towards thermally manage their batteries effectively. Tesla is in the process of patenting its indirect liquid cooling system of water-glycol coolant lines, whereas, Nissan and Toyota are committed to air cooling.

In the view to deploy fast charging, there will be a rise of power supply from 350 kWh to 500 kWh by 2030, wherein liquid cooling of batteries with fluids would allow the vehicle to be kept cool when its stationary and the batteries are in high operation. Also, this type of system allows the batteries to be raised to an optimal temperature in cold ambient conditions. However, it comes at the expense of weight, complexity, and cost.

Steps forward for battery manufacturers and automakers

For battery manufacturers, modularity of complete battery systems is a trend wherein all-in-one, plug-and-play technologies enable automakers to install battery systems quickly, requiring no previous EV system installation experience. To this end, thermal management would become a differentiating factor to success for suppliers; wherein, especially, the ability to transfer knowledge from developing traditional systems to complex hybrid systems would become significant.

With the advent of e-mobility, automakers will have to redevelop their business model to create new revenue and profit segments for EVs. In this scenario, BTMS would be a differentiating factor for various automakers as it can indirectly determine safety, durability, driving range, power yield, and quick recharging capabilities of an EV.

New materials-New frontiers

We see robust lithium-ion battery development taking place to reduce costs. As nickel and manganese are cheaper, more abundant, and safer in comparison with cobalt, the industry is finding ways to replace them with cobalt-containing materials. The industry is also looking at ways to replace the lithium ions that shuttle between the two electrodes with ions and electrolytes that may be cheaper and potentially safer. In the future, changes on these lines would further open-up new frontiers for new battery thermal management systems.

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