Silicon Carbide for Sustainable Transportation

Powering industrial e-mobility across land, sky, water, and rail

Following closely behind the adoption of electric vehicles, new transportation markets are transitioning to electric mobility (or e-mobility) to achieve a sustainable, CO_2-neutral future. From commercial electric vehicles to advanced air mobility, long-haul ships, and high-speed trains, new electrified vehicle concepts are emerging all around the world. But what does it take to enable industrial e-mobility? The latest innovations in silicon carbide technology can provide reliable, efficient, and cost-effective energy conversion and delivery.

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The term e-mobility, also known as electric mobility or electro-mobility, refers to the use of electric propulsion to drive a vehicle. Wide bandgap semiconductors like silicon carbide are used in vehicle inverters to manage the transfer of power from the energy source (e.g. battery or hydrogen fuel cell) to the electric motor. Although most widely associated with passenger electric vehicles (EVs), Wolfspeed expands the term to "industrial e-mobility" to encompass the range of applications across land, sky, water, and railway that run on all types of electric platforms.

While some industrial e-mobility segments are emerging, such as electric vertical take-off and landing (eVTOL) aircraft, others, like electric railway, are well established. Manufacturers within each segment are working to transition from traditional mechanical solutions to electrified systems that can increase power, improve efficiency, and reduce carbon dioxide (CO_2) emissions from transportation.

The ratio of vehicle electrification is growing across all transportation segments. Currently, 19% of EVs[1], >10% of construction and agriculture vehicles[2], 1-2% of water vehicles[3], and 45% of aircraft[4] are fully and partially electrified. These segments are growing at CAGRs of 20% for EVs[5], 21.5% for construction and agriculture vehicles[6], 12.7% for water vehicles[7], and 13% for aircraft[8] from about 2023 to 2030.

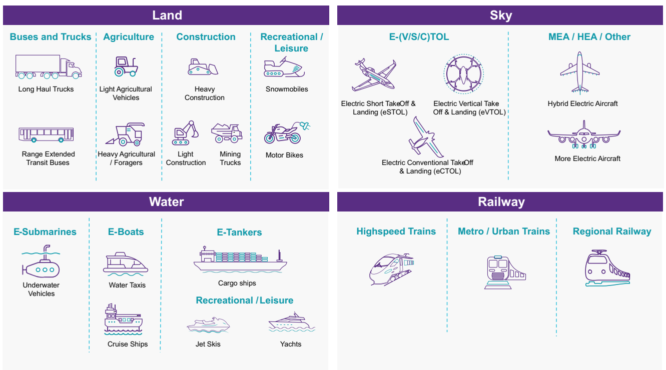

Figure 1: Examples of industrial e-mobility applications within land, sky, water, and railway markets.

Moving to Industrial E-Mobility

Two driving factors have prompted the rapid and widespread shift to vehicle electrification.

Driving Factor #1: Global Targets for Emissions Reduction

Transportation accounts for 20% of global carbon dioxide emissions, producing approximately 7.6 $GtCO_2$ a year[9]. This is primarily due to the burning of diesel and gasoline within internal combustion engine (ICE) vehicles. Although passenger cars and vans are the leading source of emissions, freight, shipping, aviation, and railway all contribute to the total environmental impact.

Therefore, governments worldwide are implementing increasingly stricter regulations (and offering new incentives) to curb emissions and accelerate the production of sustainable transportation. These regulations focus on reducing greenhouse gas emissions within given transportation segments. For example, the EPA Cleaner Trucks Initiative in the United States, PE-CONS 60/19 in the European Union, and VI Fuel Standards in China all set CO2 emissions performance standards for new light- and heavy-duty construction and agriculture vehicles.

Furthermore, the International Maritime Organization has implemented regulations to cut down greenhouse gas emissions from ships, including the Marine Environment Protection Committee (MEPC 80) session that targets a 40% reduction in CO2 emissions from international shipping[10]. The Energy Efficiency Design Index requires a maximum energy efficiency level for different ship types and size segments. This equates to a 30% CO2 reduction level for new builds in 2025 compared to the 2000-2010 average[11]. Other organizations including the International Civil Aviation Organization, European Union Aviation Safety Agency, Federal Aviation Administration, and Civil Aviation Administration of China all set emissions standards for aircraft.

In order to reduce emissions and adhere to these types of regulations, industrial e-mobility markets depend on the benefits of electrification: energy efficiency and zero emissions.

Driving Factor #2: Innovations in Power Semiconductors

Industrial e-mobility applications require reliable and efficient solutions to manage high voltages and currents under demanding environmental conditions. Compared to silicon, silicon carbide devices enable higher switching frequencies and greater power densities at much higher operating temperatures – which are all necessary for high-power industrial e-mobility applications.

Wolfspeed's release of automotive qualified (AEC-Q101) silicon carbide MOSFETs enabled manufacturers to begin the transition from ICE to electric vehicles. And starting in 2019, the release of higher power silicon carbide power modules, including the XM3 product family from Wolfspeed, enabled DC fast chargers to

Product SKU	Configuration	Blocking Voltage	Current Rating	RDS(ON) at 25°C	Maximum Junction Temperature	Qualification
CAB320M17XM3	Half-Bridge	1700 V	320 A	3.5 mΩ	175 °C	Industrial
CAB400M12XM3	Half-Bridge	1200 V	400 A	4 mΩ	175 °C	Industrial
CAB425M12XM3	Half-Bridge	1200 V	425 A	3.2 mΩ	175 °C	Industrial
CAB450M12XM3	Half-Bridge	1200 V	450 A	2.6 mΩ	175 °C	Industrial
EAB450M12XM3	Half-Bridge	1200 V	450 A	2.6 mΩ	175 °C	Automotive

Table 1: Wolfspeed XM3 silicon carbide power module family

achieve a full charge in less than 4 minutes, making EV adoption more appealing and affordable for consumers. Automotive OEMs like General Motors, Lucid Motors, Jaguar Land Rover, Mercedes, and others continue to announce significant electrification plans for next generation EVs (including the transition from 400 V to 800 V power distribution architectures). State-of-the-art industrial e-mobility applications are following closely behind these developments, relying on technological innovations in silicon carbide to provide higher power density, higher system efficiency, and longer range, along with lower system cost and long-term reliability.

Industrial E-Mobility Case Study: Electric Water Vehicles

Let's take a closer look at how the benefits of silicon carbide can enable new developments in electric water vehicles ranging from jet skis and yachts to passenger ferries, water taxis, harbor craft, cargo ships, tankers, and submarines.

Half-Bridge Power Module Designed to Enable High Power Density

Wolfspeed developed the XM3 power module platform to maximize the benefits of silicon carbide while keeping the module and system design robust, simple, and cost effective. With half the weight and volume of a standard 62 mm module, the XM3 power module maximizes power density while minimizing loop inductance and enabling simple power bussing. The optimized packaging enables 175°C continuous junction operation, with a high reliability silicon nitride (Si_3N_4) power substrate to ensure mechanical robustness under extreme conditions. The XM3 is a perfect fit for demanding applications such as industrial e-mobility main inverters.

Within the main inverter of a water vehicle, XM3 power modules enable significant system-level optimization. Design engineers can increase power density without increasing system size by moving from a 200 kW [powered by the CAB400M12XM3] to 300 kW [powered by the CAB450M12XM3] inverter.

We used a 200 kW three-phase inverter reference design [200kW Three-Phase Inverter with XM3 Power Module | Wolfspeed] to compare silicon carbide power modules to silicon IGBTs.

This inverter design features a complete stack-up including modules, cooling, bussing, gate drivers, voltage / current sensors, and controller, and can be used in conjunction with Wolfspeed's SpeedFit Design Simulator tool [SiC and GaN Solutions SpeedFit Design Simulator | Wolfspeed] and Power Applications Forum [Wolfspeed Power Applications Forum].

a) Comparing efficiency vs output power using Wolfspeed's 200 kW three-phase inverter
b) Comparing inverter losses vs output power using Wolfspeed's 200 kW three-phase inverter

Overall, silicon carbide enables higher power, greater efficiency, lower switching losses, and higher switching frequency, within a lighter weight, smaller system.

	Wolfspeed SiC 200 kW inverter CRD200DA12E-XM3	Wolfspeed SiC 300 kW inverter CRD300DA12E-XM3
Weight	6.2 kg	6.2 kg
Volumetric power density	21.7 kW/liter	32.25 kW/liter
Efficiency	98.28%	98.3%

Table 2: Comparing a 200 kW to 300 kW silicon carbide inverter.

The Electrification of Everything Inside Industrial E-Mobility

In addition to main inverters for battery electric vehicles (BEVs) and fuel cell inverters for fuel cell electric vehicles (FCEVs), industrial e-mobility applications can integrate power electronics within battery management systems (BMS), auxiliary power supplies, auxiliary power drives, pump and fan actuators (HVAC systems), and onboard chargers. Each electrified system further reduces the number of mechanical components compared to ICE vehicles, enabling greater efficiency, lighter weight, and lower total cost of ownership.

Figure 2: Wolfspeed XM3 silicon carbide power module.

Figure 3: Wolfspeed 200 kW XM3 three-phase inverter.

These electrified systems conserve system-wide energy usage, reduce emissions, and extend lifetime through low losses, high power density, and high reliability and robustness. However, the operating environments of industrial e-mobility applications, including temperature fluctuations, vibration, high humidity, and harsh climates, impact which systems benefit most from electrification.

For example, water vehicles may integrate electric elevators, cranes, anchor winches, and automation systems, in addition to the main inverter.

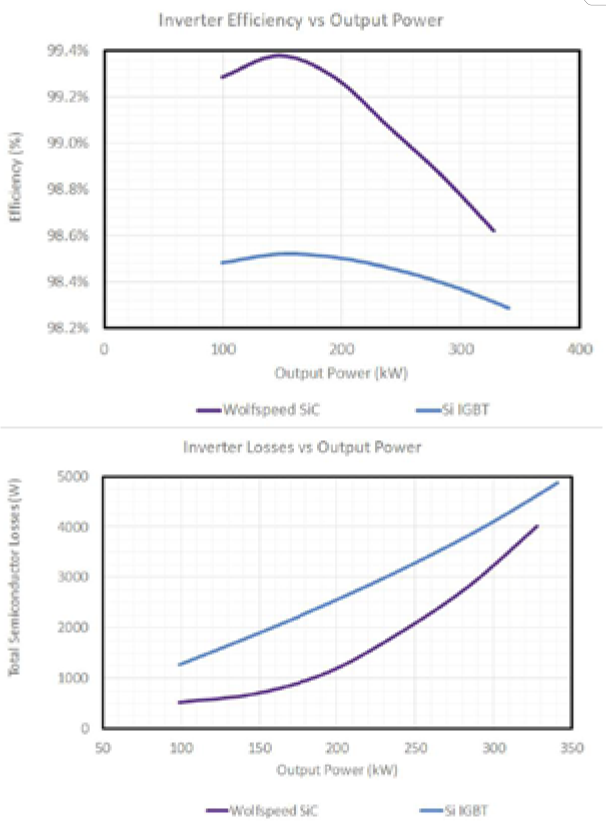

Figure 4: Comparing the simulated efficiency and switching losses between a Wolfspeed silicon carbide 200 kW power module [CAB-400M12XM3] and a silicon 200 kW IGBT for a water vehicle 800 V main inverter.

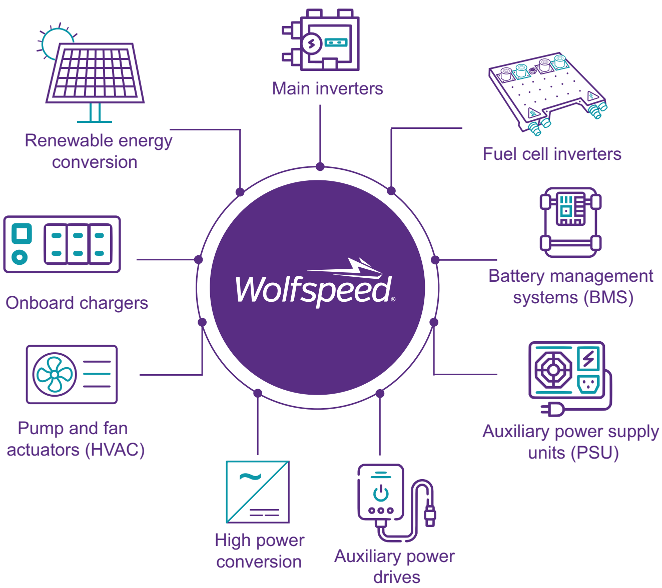

Figure 5: Power electronics systems within industrial e-mobility applications

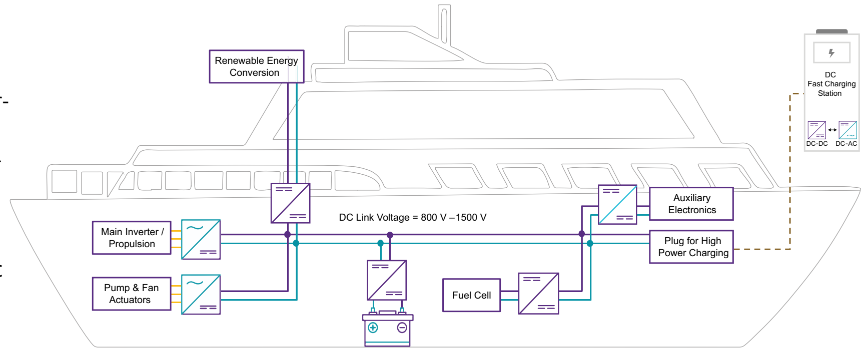

Figure 6: Example power electronics systems within water vehicles that can benefit from silicon carbide devices.

Numerous systems can also be electrified within off-highway land vehicles, which range from small forklifts to megawatt-consuming mining trucks. For example, electrical power take-off (ePTO) drives can lessen the load on the main inverter within heavy-duty construction and agriculture vehicles by harnessing and distributing power to auxiliary functions. And lower-power inverters can replace existing mechanically driven systems such as fans, pumps, actuators (HVAC) and thermal management systems.

Advanced air mobility applications can integrate a series of smaller, more efficient electronics systems that can lower weight and conserve space inside vehicles where size, weight, and power (SWaP) ratios matter most. Electric spoiler controls, solid state power controllers, circuit breakers, de-icing systems, and green taxing systems are key systems within these vehicles. The lighter weight and smaller size achieved by integrating power electronics within these auxiliary systems translates into extra range and/or extra cargo capacity.

Finally, regional, metro, and high-speed railway applications operate at high voltages, sourcing power that is distributed from a grid to overhead (or under rail) lines. Trains can also incorporate electric power systems for door control, braking, and energy recuperation within battery and grid designs. Each of these systems require reliable and efficient power semiconductors to supply and manage electrical switching. Silicon carbide is the best-in-class technology for the voltage classes required by not only the main inverter, but also the wide range of auxiliary power supplies and drives essential within industrial e-mobility applications.

Challenges Facing the Future of Industrial E-Mobility

Two of the biggest challenges for the future of industrial e-mobility are energy sources and infrastructure. All electric vehicles require an energy source—most commonly a battery or hydrogen fuel. Industries have already recognized the rising demand for both. According to the International Energy Agency, battery production will increase 400%[12] and hydrogen production will increase by >18%[13] from 2023 until 2030.

In addition to a larger quantity of batteries, industrial e-mobility will require more powerful batteries to get the required energy density within the same space (more watt hours per kilogram). Batteries with higher power density are better suited to vehicles with higher power inverters such as heavy-duty construction vehicles and cargo ships. These battery and hydrogen market developments are essential to the future of industrial e-mobility.

Infrastructure—high power charging stations, electric grid capacity, and hydrogen refueling stations—is also crucial.

Regional and local governments are investing in charging stations to boost EV adoption, but expanding, scaling, and maintaining efficient, fast, and high-power charging infrastructure is a substantial undertaking. For EVs, this means roadside superchargers.

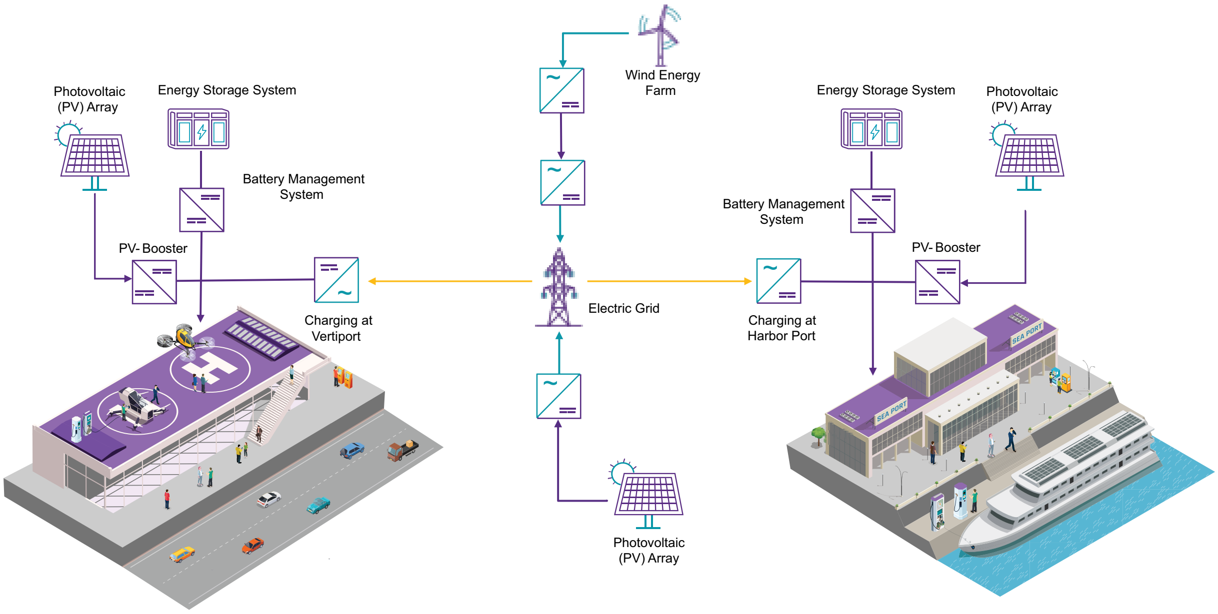

Figure 7: Renewable energy sources can support upcoming high-power charging infrastructure at vertiports and harbors.

For long-haul trucks, this means megawatt charging system (MCS) technology. For regional buses, this means depot charging. For ships, this means charging at harbor ports. For aircraft, this means charging at vertiports.

Wolfspeed's Long-Term Vision for the Industry

Wolfspeed is leading the transition from silicon to silicon carbide as we enable the industry through a growing number of product portfolios that scale from less than 2 kW up through the megawatt range and address a broad range of voltage, current, and isolation requirements.

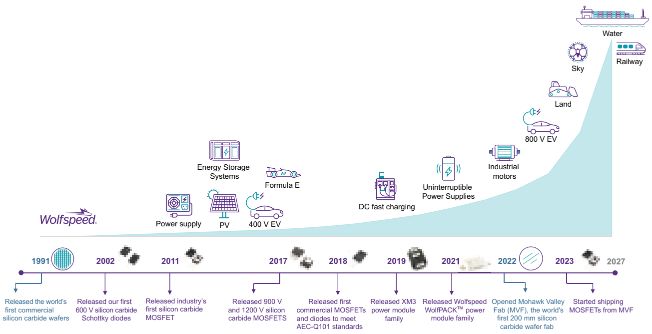

Figure 8: Wolfspeed's innovations in silicon carbide materials and devices have enabled many different markets, including advancements in industrial e-mobility.[14]

From now until 2027, we expect a significant percentage of the silicon carbide device market to come from industrial and energy applications, including industrial e-mobility.

For more than 35 years, Wolfspeed has focused on producing vertically integrated silicon carbide wafers and high-quality power devices in our mission to save the world energy. To-date, Wolfspeed has manufactured more than 60% of the world's silicon carbide. Our silicon carbide devices have surpassed 12 trillion field hours. We have a global footprint of support. And we can work directly with manufactures to develop high-performance silicon carbide products that are optimized for the specific requirements of industrial e-mobility applications.

Wolfspeed is scaling our capacity to meet the surge in demand for reliable and efficient energy conversion and power delivery solutions. In 2022, we opened the world's first and largest 200 mm silicon carbide fabrication facility in Marcy, New York. This state-of-the-art power wafer fab will be automotive-qualified and has already started shipping MOSFETS. It is complemented by our materials factory expansion at our Durham, North Carolina headquarters, our upcoming materials manufacturing facility in Siler City, North Carolina, and the world's most advanced silicon carbide device manufacturing facility planned for Saarland, Germany. These investments are necessary to support the rapid growth of industrial e-mobility applications, meet the climate goals of nations around the world, and achieve sustainable electrification.

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