Battery and Electric Drive Components for Low-carbon Society

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TRENDS IN BATTERY AND ELECTRIC DRIVE COMPONENTS

Role of Battery and Electric Drive Components

THE environment has become a serious problem at the global level in recent years and countries around the world have embarked on activities aimed at realizing a low-carbon society capable of striking a balance between global warming prevention, CO_2 (carbon dioxide) emissions reduction, and other measures for dealing with these environmental problems on the one hand and social progress and economic growth on the other.

In Japan, the "New Growth Strategy (Basic Policies)" approved by the cabinet in late 2009 looks ahead to 2020 and establishes green innovation (innovation in the environment and energy fields) as a growth industry that draws on Japan's strengths. The policy identifies the necessity of achieving social progress and economic growth through active promotion of green innovation and by leading the world in finding solutions to these problems.

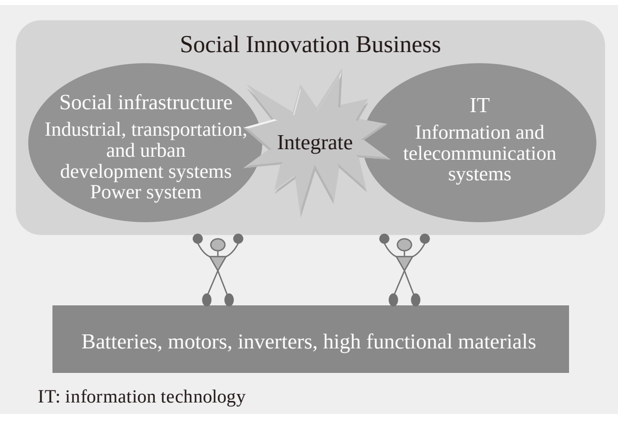


Fig. 1—Key Components that Support Hitachi's Social Innovation Business.
Hitachi offers solutions that integrate its skills in the building of social and industrial systems with batteries and electric drive components.

Similarly, Hitachi is seeking to focus its efforts on its Social Innovation Business by integrating the latest information and telecommunication systems technology with social infrastructure such as the power system, industrial, transportation, and urban development systems, and to contribute through Hitachi products and services to a 100-million-t reduction in annual CO_2 emissions by 2025.

Hitachi also sees battery and electric drive components (electric motors and inverters) as having a key role in supporting these products (see Fig. 1).

Market Environment for Green Society

To achieve the target of halving global CO_2 emissions by 2050 relative to the 2005 total of 28 billion t, it is estimated that total global investment in countermeasures will need to have expanded to 92 trillion yen by 2025. At 66 trillion yen, the adoption of hybrid, electric, or other advanced drive mechanisms in cars, trains, ships, aircraft, and other transport equipment makes up the largest component of this total, followed by spending of 11 trillion yen on new energy sources for electricity generation and general industry (see Fig. 2). Accordingly, it is anticipated that the shift toward this green society will be accompanied by significant growth in the market for battery and drive components.

Reducing energy consumption has an important role in preventing global warming and reducing CO_2 emissions. This means reducing electricity consumption by improving the energy efficiency of electric motors which are a key component in many products and reducing energy consumption by replacing electric motor systems (integrated systems that combine motors, inverters, and batteries) in systems that are currently powered by mechanisms such as engines or hydraulics. Other possibilities include creating an environment that can make extensive use of new energy sources, such as wind or solar power generation

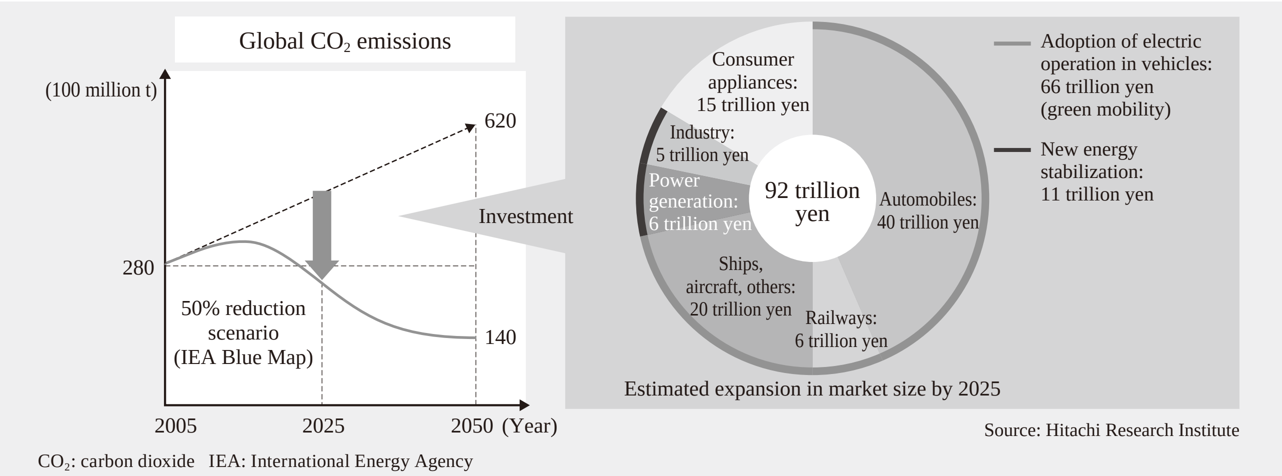


Fig. 2—Market Expansion Accompanying Shift to Green Society.
It is anticipated that the shift to a green society will significantly expand the market for battery and drive components.

systems that use batteries to stabilize their output, by operating these as part of the electricity grid.

Trends in Motor Energy Efficiency

Electric motors consume approximately 40% of all electricity generated globally. To promote energy efficiency, the International Electrotechnical Commission (IEC) published the IEC60034-30 standard which stipulates efficiency classes for induction motors operating at constant speed. Fig. 3 shows the IEC guidelines (IE1 to IE4). Each level requires that motor losses be reduced by 15% compared to the level below such that, for example, IE2 stipulates a 15% reduction in motor losses compared to IE1. Achieving IE3 will be a requirement in the USA by 2011 and in Europe by 2014. Japan issued a JIS (Japanese Industrial Standards) C4034-30 equivalent to IEC in 2010.

For an idea of the savings that are possible, consider the case when an IE1 induction motor (7.5 kW) running at constant speed is replaced by an IE3 permanent magnet motor. Assuming that both motors are under inverter control, the savings in annual CO_2 emissions from replacing the permanent magnet motor are 1.9 t (10%).

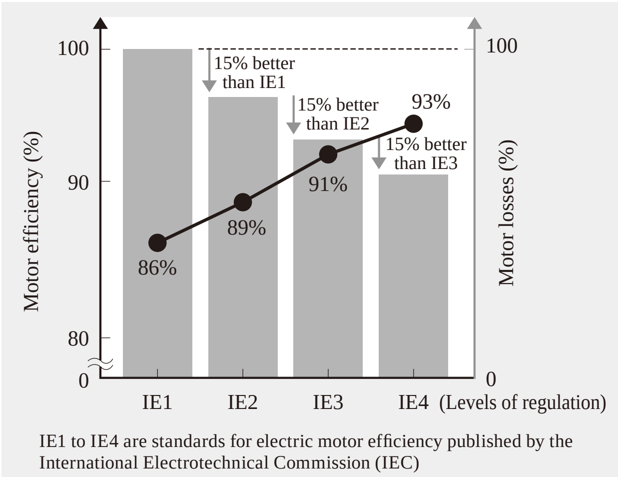


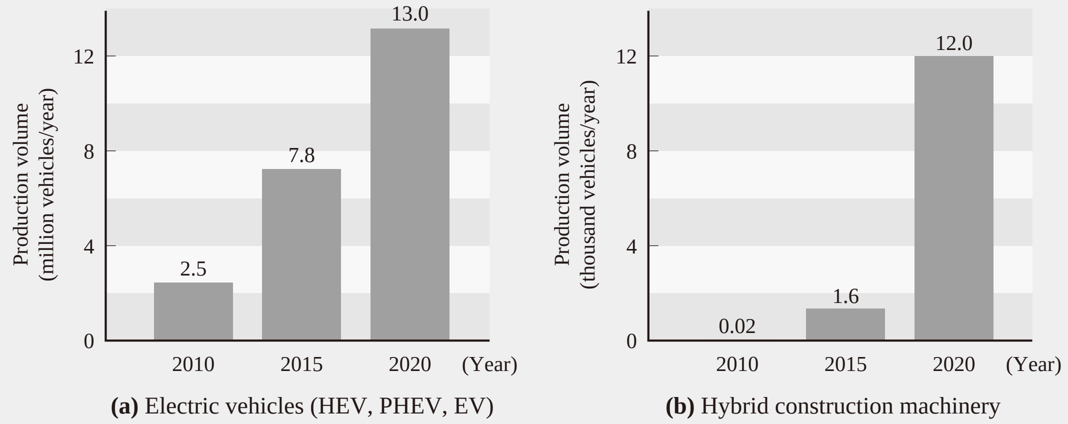
Fig. 3—International Energy Efficiency Standard for Induction Motors.
Each level represents a 15% reduction in losses compared to the level below.

Motor System for Use in Electric Drive Applications

The trend toward adopting electric drive in systems that previously used engines, hydraulics, or other similar mechanisms already has considerable momentum (see Fig. 4). With the US CAFE[(a)] scheme to offer credits for PHEVs (plug-in hybrid electric vehicles) from 2012, it is anticipated that use of PHEVs will grow in a similar way to HEVs (hybrid electric vehicles). In construction machinery, meanwhile, the expectation is that hybrid construction machinery will become more common from 2015 to 2020 due to the strengthening of regulations applying to diesel engine exhaust from 2015.

The adoption of electric drive involves more than just replacing engines or hydraulics with electric

(a) CAFE
CAFE is an abbreviation of "corporate average fuel efficiency." A regulation applying to cars and trucks sold in the USA that calculates the mean fuel consumption of each automobile manufacturer's product range and requires that this does not exceed the standard limit. The regulation applies to all companies that sell vehicles in the US market. The standard for passenger cars up to 2007 was 27.5 miles per gallon (11.7 km/l) and the US government has announced its intention to increase this to 35.5 miles per gallon (15.1 km/l) by 2016.



Source: Hitachi research

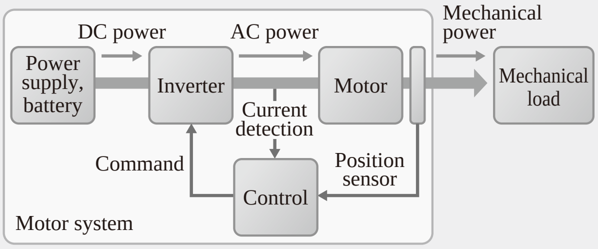
HEV: hybrid electric vehicle PHEV: plug-in hybrid electric vehicle EV: electric vehicle

Fig. 4—Market Forecasts for Adoption of Electric Drive.
Growing use of electric drive in vehicles that previously used engines or hydraulics will result in a large market by 2020.

motors, it also entails knowing how to use the motor appropriately. Treating the motor as a system, in other words. Fig. 5 shows the basic configuration of an electric drive system. The DC (direct current) output of the power supply and batteries is converted to AC (alternating current) by an inverter and supplied to the motor which in turn converts the electric energy into mechanical energy to drive the load.

The first consideration for appropriate motor use is energy saving and it is recommended to use permanent magnet motors which combine high efficiency with small size. The second consideration is efficiency improvement which seeks to improve the overall energy conversion efficiency including both the motor and inverter. The third consideration is to improve performance and, with the responsiveness of an electric motor being about 100 times faster than an engine, the key system consideration is how to achieve high performance in controlling the mechanical load.

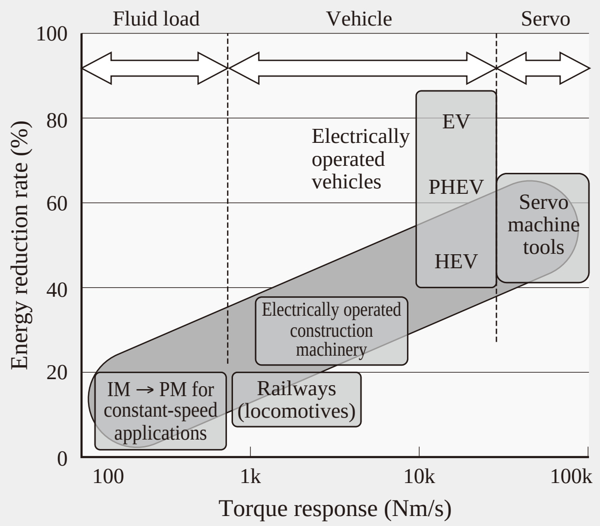
Fig. 6 shows the results of a survey into the energy savings achieved when electric operation was adopted



System-oriented approach	
Energy saving	Use of permanent magnet motors and smaller motors
Efficiency improvement	Improvements to inverter energy conversion (DC → AC)
Performance improvement	Use superior responsiveness of electric motor to control mechanical load

DC: direct current AC: alternating current

Fig. 5—Basic Configuration of Electric Drive System.
Electric operation means making effective use of electric motors and taking a system-oriented approach to these motors.



IM: induction motor PM: permanent magnet motor

Fig. 6—Relationship between Torque Response and Energy Reduction Rates Resulting from Adopting Electric Drive.
Because the adoption of electric drive saves energy by performing rapid control of high torque, there is a rough correlation between energy reduction rates and torque response.

based on information from projects in a range of different industries. The figure shows the correlation between energy savings and torque response. Servo machine tools which have the fastest response can control torque output by several tens of thousands of Nm in approximately 0.2 s. Large energy savings can be achieved by replacing the previous hydraulic mechanisms which operated continuously with the use of electric drive to control high levels of output over short time spans. This is a major feature of electric drive operation.

On electrically operated vehicles such as HEVs, PHEVs, and EVs (electric vehicles), the more batteries the vehicle has the greater the energy savings that can be achieved. Also, further energy savings can be achieved by using regeneration whereby the motor is operated as a generator to utilize the vehicle's kinetic energy during braking and the resulting electric power stored in the batteries for reuse in subsequent acceleration.

Attention-grabbing Lithium-ion Batteries

The technology for lithium-ion batteries was developed in Japan. Small and lightweight lithium-ion batteries have entered widespread use in recent years, particularly in consumer appliances such as mobile phones, notebook PCs (personal computers), and other portable devices.

The ability for rechargeable batteries to be repeatedly refilled with electric power and carried about has significant consequences. Behind these rechargeable batteries lies 150 years of history and past developments of other battery types including the lead-acid batteries used mainly in vehicles and backup power supplies and nickel hydride batteries used mainly in HEVs.

The reason lithium-ion batteries have attracted so much attention is due to their high energy density (endurance), small size, and light weight. When compared by energy density, lithium-ion batteries can be made with only about one-third the volume and weight of equivalent lead-acid batteries and the ratio for nickel hydride batteries is approximately one-half.

It is anticipated that the characteristics of small size and light weight that come with high energy density will see the market for the batteries expand in the future, particularly in applications like environmental vehicles (HEVs, PHEVs, EVs, and similar), electric cycles, and industrial applications such as construction machinery, and that they will be used in applications such as smart grids in the future.

However, one difficulty associated with the use of lithium-ion batteries is they are in effect electronic devices that require external control. The batteries cannot be used by itself and instead a control system is required to achieve good battery performance. Failure to control charging and discharging parameters such as speed and amount of charge can result in excessive heat generation. That is, lithium-ion batteries can be thought of as electronic devices from which a high level of energy storage performance can be achieved safely by implementing an appropriate control system.

HITACHI'S INVOLVEMENT IN BATTERY AND ELECTRIC DRIVE COMPONENT MARKET

Involvement in Electric Drive Businesses

Hitachi celebrated the 100th anniversary of the company's founding in 2010. Its first product in 1910 was a 5-HP (horsepower) (3.7-kW) induction motor. Fig. 7 shows Hitachi's current electric drive businesses. Hitachi produces motors and associated equipment for industry, home appliance and consumer products, the automotive industry, construction machinery, power systems, and social systems (trains, elevators, and escalators). The trend in the technology of electric drives is to consider the total performance including both motor and inverter (including control) which means we are now entering an era in which motors are custom-designed for specific systems.

The trend to stronger regulatory requirements for motor efficiency is also contributing to a shift from

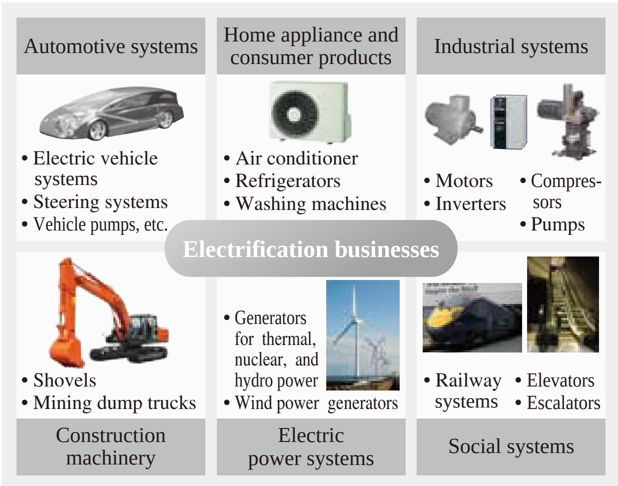


Fig. 7—Hitachi Electric Drive Businesses.
Hitachi produces motors and associated equipment for industry, home appliances and consumer products, the automotive industry, construction machinery, power systems, and social systems (trains, elevators, and escalators).

induction motors to permanent magnet motors in electric drive applications. Depending on demand, Hitachi also intends in the future to produce high-voltage permanent magnet motors (600-kW class or larger) for use in large-scale power generation, railway, and similar applications.

Harmonious Motor System

Fig. 8 shows the Harmonious Motor System concept promoted by Hitachi for its electric drive business. Harmonious Motor System seeks to supply customers with the motor solution that best suits their needs. Future motor systems will need to satisfy both environmental and drive performance requirements and achieving this will require resolving the complex interrelationships between power supplies, batteries, inverters, motors, control, and mechanical loads.

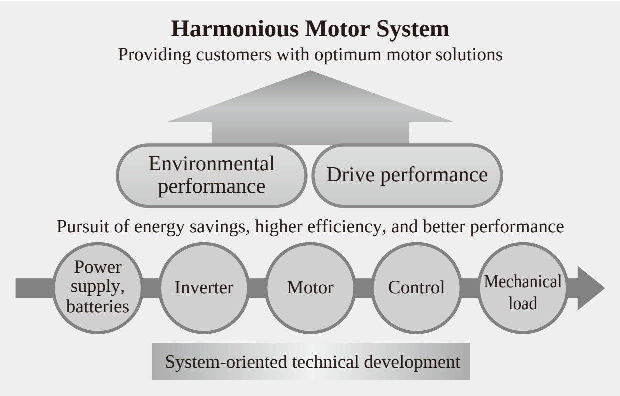


Fig. 8—Hitachi's Harmonious Motor System Vision.
Harmonious Motor System seeks to supply customers with the motor solution that best suits their needs by delivering both environmental and drive performance.

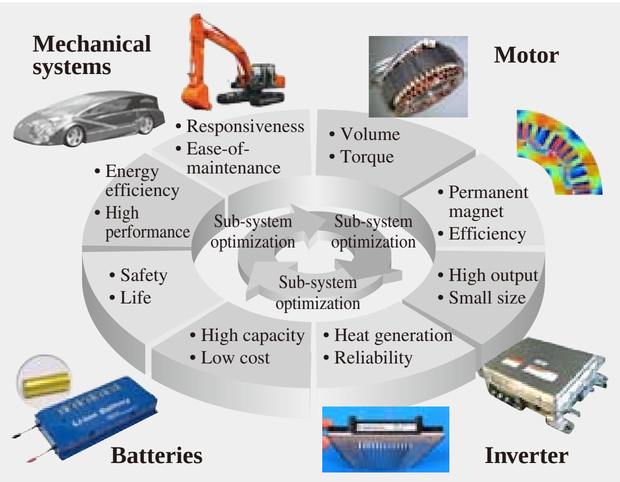


Fig. 9—Requirements and Issues for Electric Drive Components.
Because of the potential for optimization of one component to cause problems for other components, what is required is a harmonious solution that suits the entire system.

Fig. 9 shows the requirements and issues associated with motors, inverters, batteries, and mechanical loads. For motors that need to combine small size with high torque, the issues are with efficiency and how to make use of permanent magnets. Whereas the greater the number of magnets the lower the current in motors that need to produce high torque at low speed, higher speeds cause the magnets to generate an EMF (electromotive force) which degrades the efficiency because a higher current is needed to counteract this effect. Also, while sub-system optimization in which problems are resolved by balancing the requirements and issues of the motor on its own is important from a "monozukuri" manufacturing perspective, there is the potential for sub-system optimizations of the motor to affect the inverter, batteries, or other sub-systems when the motor is combined with these other components.

High output and small size are also requirements for inverters but reliability issues can arise due, for example, to solder degradation caused when the heat generated in power devices, and life shortening of capacitors and other components caused by the temperature rise. On the other hand, it is possible to incorporate functions for controlling electric power in the inverter and reduce the losses that cause this heat generation. Achieving this requires consideration of the motor and batteries also rather than attempting to optimize the inverter on its own.

The shift from HEVs to PHEVs and then to EVs requires progressively higher output and larger capacity from the batteries. Safety and battery life are issues and the battery specifications that determine these are in turn decided by the requirements of the drive and electric power systems which include the mechanical load, motor, and inverter. Although standalone improvements to the safety and longevity of batteries are important, using the energy demand for the entire system as a starting point for the design leads to greater overall efficiency.

The desired approach is to classify the various different problems from the mechanical load down to the individual components and then to propose a solution that strikes a harmonious balance between these different challenges. This requires analysis technology capable of performing integrated design of the power supply, battery, inverter, motor, control, and mechanical load together with control technology able to balance the requirements of different components.

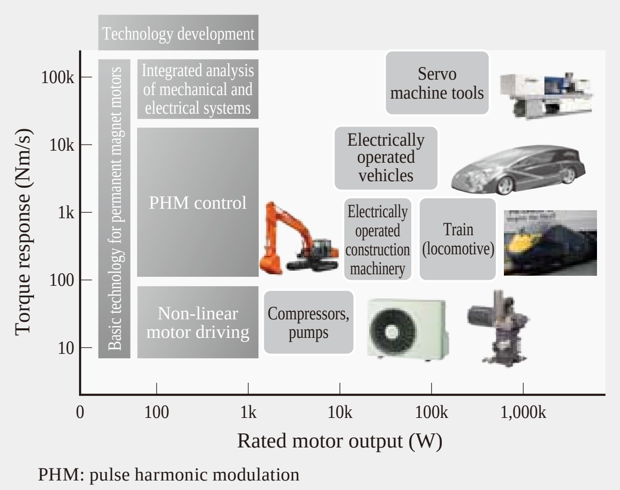


Fig. 10—Control and System Technologies under Development for Harmonious Motor System.
Analysis techniques able to perform integrated design of the power supply, battery, inverter, motor, control, and mechanical load are under development together with control techniques able to strike a harmonious balance between the issues for different components.

Fig. 10 shows the control and system technologies currently under development to implement the Harmonious Motor System. Rather than performing sub-system optimizations of individual components, the aim is to find control- and system-based ways of dealing with multi-faceted problems that span different components. Simulation technology is being developed to perform an integrated analysis of the mechanical load and motor system for fast-response servo applications, while PHM[b] is being developed to boost the efficiency of vehicles by improving the efficiency of the motor, inverter, and battery as an integrated system. Other developments include non-linear motor driving[c] to help reduce the size and cost of motors and inverters for compressors and pumps where slow response is not a problem, and basic technology for permanent magnet motors that is applicable to all applications.

High Functional Materials for Building Smaller and More Efficient Motors

Research into the materials used in motors is also underway with the aim of making motors smaller and more efficient. The research is investigating the main materials used in motors which include permanent magnets, core materials, wire, and impregnated varnish. The research topics for each of these are described below.

For permanent magnets, the research is aimed at further improving the performance and reducing the cost of Nd-Fe-B (neodymium-iron-boron) sintered magnets. For motor core materials, the work includes developing and commercializing amorphous metals with low iron losses and high magnetic permeability. Wire research includes development of enamel wire with strong heat tolerance, improving the slot packing density (higher packing density), improving the adhesion of impregnated varnish, and ensuring that the wire can withstand high-voltage operation when under inverter control. Research on impregnated varnish is seeking to reduce use of VOCs (volatile organic compounds) and improve heat tolerance.

Whereas it was common in the past when designing materials to base decisions such as the material composition and structure on experiments alone, recent advances in computing science and computational capacity have led to attempts at using simulation to design new materials.

Involvement in Lithium-ion Battery Business

Hitachi has been developing lithium-ion batteries for HEVs in conjunction with motors and inverters since the 1990s and has led the world in mass producing and bringing to market lithium-ion batteries with high performance and long life.

Hitachi is also strengthening its battery business targeted at industrial applications with automotive lithium-ion batteries playing a core role. Alongside the expansion of the business that sells standalone battery cells, Hitachi is also strengthening its energy storage solutions business including offering solutions that draw on its system application. In the railway sector, Hitachi has already combined the extensive experience and know-how it has built up in the industry with its automotive lithium-ion batteries to implement hybrid drive systems and has commercialized an electric

(b) PHM control (drive control technique using harmonic modulation and fewer pulses)
PHM is an abbreviation of "pulse harmonic modulation." A new control technique developed by Hitachi to improve the efficiency of automotive and other motors when operating at high speed. PHM can reduce heat generation in the inverter by up to 40% and improve motor output by 10% at high speed by using only one-fifth as many pulses as conventional PWM (pulse width modulation) control and reducing current waveform distortion.

(c) Non-linear motor driving
A control technique that approximates the relationship between current and magnetic flux by a non-linear function, taking account of the fact that making motors smaller makes them more prone to magnetic saturation (a characteristic of magnets whereby increasing the current no longer increases the magnetic flux and output saturates). Non-linear motor driving allows motors for compressors and pumps to be made up to 20% smaller while still maintaining high efficiency.

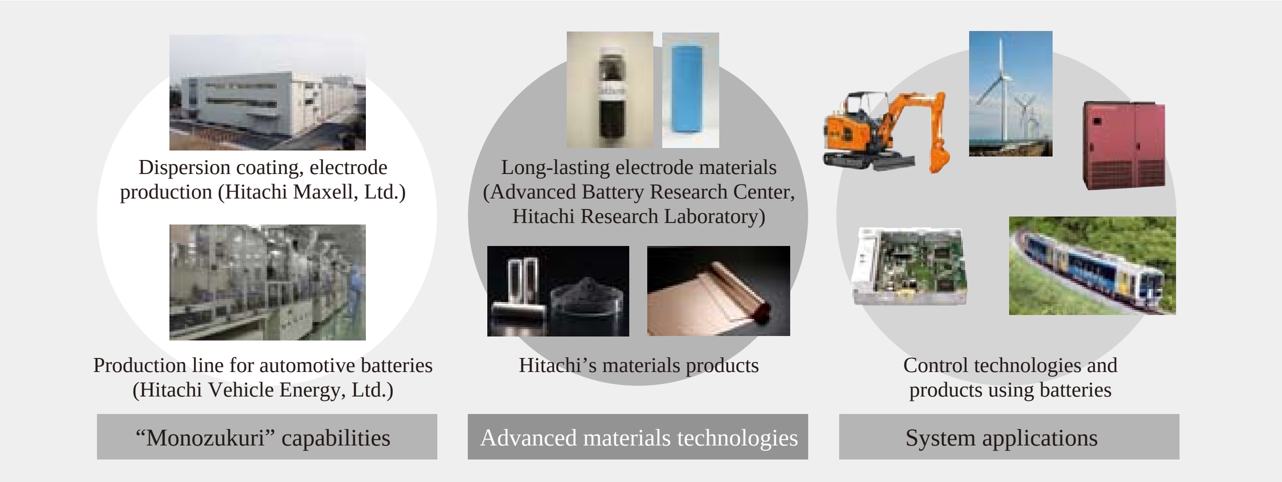


Fig. 11—Basic Technologies that Support Hitachi's Battery Business.
Hitachi's strengths are its "monozukuri" manufacturing capabilities, advanced materials technologies, and system applications. The long-life battery materials were the result of research sponsored by the New Energy and Industrial Technology Development Organization (NEDO).

power regeneration system with a battery storage capability that makes effective use of regenerative electric power.

A feature of Hitachi's battery business is that it deals with batteries for a wide range of different applications extending from consumer lithium-ion batteries for devices such as mobile phones and game consoles; lithium-ion batteries for HEVs and PHEVs; large industrial lithium-ion batteries for backup power supplies; and long-life lead-acid batteries for electricity storage. Hitachi also has other business divisions within the group that handle the design and manufacture of products ranging from electrode materials for lithium-ion batteries to battery cells, battery packs, and control systems as well as equipment, systems, and solutions that utilize batteries. In other words, Hitachi's strengths lie in its "monozukuri" manufacturing capabilities, advanced material technologies, and system applications (see Fig. 11).

An example of Hitachi's "monozukuri" manufacturing strength is that the dispersion coating techniques built up through long experience in the production of magnetic tape form the basis of its high-performance and highly reliable electrode technology. In the field of automotive lithium-ion batteries, Hitachi has delivered more than 1.2 million cells to date and vehicles using Hitachi batteries have already been on the road for five years.

Hitachi's advanced material technologies are developed by its research and development divisions which have notched up notable achievements including the successful development of a positive electrode (cathode) material that helps extend battery life. This was the product of research sponsored by the New Energy and Industrial Technology Development Organization (NEDO).

Regarding system applications, Hitachi aims to collaborate within the group to strengthen its industrial battery business operations by combining control technology for achieving maximum battery cell performance with its extensive experience and know-how built up in the field of battery-using products.

Business Strategy of Power Supply Solutions Business

The business strategy of the power supply solutions business is to offer solutions that draw on the system applications of the wider Hitachi Group based around the high-performance, long-life automotive lithium-ion batteries that Hitachi developed ahead of the rest of the world, and to expand into new applications. Hitachi also recognizes the importance of improving the performance of the batteries themselves (see Fig. 12).

Currently, Hitachi is mass-producing second-generation automotive lithium-ion batteries for use in HEVs that have an output power density (instantaneous power) of 2,600 W/kg. It has developed third-generation HEV batteries with an output power density of 3,000 W/kg through improvements to materials, structure, and other aspects of battery design to meet the need for higher HEV performance, and has completed a production line with a capacity of 300,000

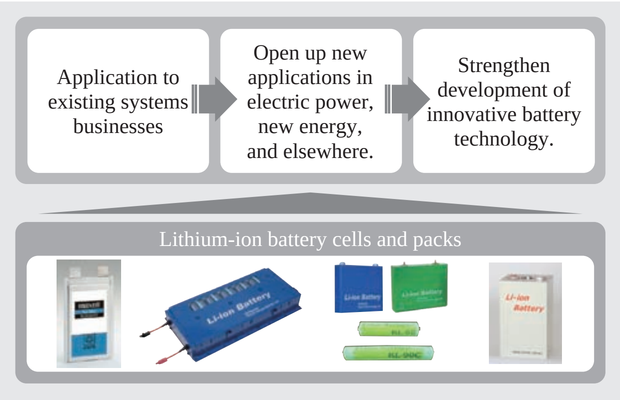


Fig. 12—Business Strategy of Power Supply Solutions Business.
In addition to improving battery performance, Hitachi also intends to open up new applications by strengthening the collective system applications of the Hitachi Group.

cells per month. Meanwhile, fourth-generation HEV batteries with an output power density of 4,500 W/kg are currently under development with the aim of achieving high output and heat dissipation, along with PHEV batteries with high energy (for EV operation) and high output power (for HEV operation).

Hitachi has considerably extended the life of lead-acid batteries developed to improve the reliability of the electricity supply to 3,000 or 4,500 cycles. It has also developed lead-acid batteries that have an expected life of 17 years when used to smooth fluctuations in wind power generation by using the batteries in ways that incorporate life-extension technologies and through appropriate management of operating conditions.

Also, large-capacity lithium-ion batteries designed for float-charge applications and developed for use in backup power supplies for communications equipment have achieved excellent performance in terms of fire retardance and operating life.

The growing sophistication of mobile devices is driving demand for larger battery capacities. The use of new active materials is one approach to improving battery capacity and improvements are being made to silicon-based anode materials and oxide-based cathode materials. Hitachi is also developing a ceramic separator to ensure battery safety which is needed because safety and high capacity are conflicting objectives. Development of small- to medium-sized industrial lithium-ion batteries is also in progress based on these battery materials and process technologies developed for portable batteries. Hitachi has released cylindrical batteries for use in electric power tools and is developing a large-capacity laminated battery with a capacity of 10 Ah.

The development of innovative battery technologies will be essential to the future development of large lithium-ion batteries. Being able to combine high output power density and high energy density together with longer life and lower cost is important. Past technical development of battery materials has included the development of innovative technologies that have produced genuine results including manganese-based cathode materials that provide long life and carbon-based anode materials that provide significant improvements in rapid charging performance, electrolytes with excellent low-temperature properties and low resistance, and electrode structure designs suitable for large batteries.

HELPING REALIZE LOW-CARBON SOCIETY

As this article has explained, urgent action is needed at a global level to combat environmental problems. Hitachi intends to continue making a contribution to the creation of a low-carbon society by improving the performance of the battery and drive components that have a key role in supporting its Social Innovation Business and by collaborating within the group to offer solutions that draw on its system application for integrating these components.

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