The Road to Liquid Hydrogen Electric Vehicle Powered by High-Temperature Superconducting Motor

– Utilizing Tank Trucks to Deliver LH_2 –

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The 21st century is “the era of energy, resource and environment.” In the near future, an increasing population and advanced civilization will urge us to rely on solar-originated new energy sources. More specifically, hydrogen (H_2) energy generated by solar cell power will assume an important role to power vehicles, the most convenient products of modern civilization. The H_2 energy will be delivered in liquid form by tank trucks to H_2 stations, where the liquid hydrogen (LH_2) will be supplied to every automobile.

Meanwhile, high-temperature superconducting (HTS) materials and technologies have markedly developed. By utilizing such application technologies as Sumitomo Electric’s cutting-edge BSCCO, an ideal hybrid electric vehicle (HEV) will be practical. LH_2, which produces 20 K cool energy, can act as a coolant itself for an HTS motor and therefore, a cooling device will not need to be mounted any more.

Thus, LH_2 holds high potential for realization of an energy-efficient environmental-friendly compact HEV, and therefore LH_2, besides high-pressure H_2 gas, should be included within the development policies for the HEV.

Keywords: HTS HEV, Sun-originated LH_2, LH_2 Tank Truck, LH_2 station, LH_2 HTS HEV

1. Introduction

The automobile is one of the most convenient products of modern civilization, and the number of vehicles is rapidly increasing as the human population continues to grow and developing countries become more economically active. From the standpoint of “energy, resources, and environmental conservation,” however, the ongoing wave of motorization has brought with it a number of problems, including the exhaustion of resources stemming from rising fossil fuel consumption and the rapid deterioration of the environment caused by greenhouse gases, which are contained within automobile exhaust (CO_2 from automobile exhaust accounts for approximately 25% of gross CO_2 emissions) (6)-(8). This being the case, almost all automobile manufacturers have developed for commercial use electric vehicles (EVs) or hybrid electric vehicles (HEVs) using an electric motor, out of consideration for the earth’s natural resources and the environment (14), (19). Presumably, the ultimate results of such efforts are fuel cell electric vehicles (FC EVs) or hydrogen engine vehicles, both of which make use of hydrogen (H_2) as fuel (9), (10). Meanwhile, dramatic progress in high-temperature superconducting (HTS) technology in recent years (1)-(3), (16), (17) has revealed that electric motors wound with HTS wire, whose electrical resistance is almost zero, are optimal for motors to power moving bodies, as they produce high torque while also conserving space and energy (4), (14). Already, a prototype liquid nitrogen (LN_2) cooled HTS motor using the first-generation HTS wire (DI-BSCCO) is being tested in ships (5) and automobiles (11).

By lowering the cooling temperature, it is possible to significantly increase the permissible electrical current (Ic: Critical current) of HTS wire (7). For example, DI-BSCCO is capable of generating 200 A of Ic per HTS wire (≈ 1 mm^2) at the LN_2 temperature of 77 K (-196 °C) (2), (16). If this HTS wire is cooled using LH_2 with a temperature of 20 K (-253 °C), its Ic can be increased by approximately six times (200 A x $6 > 1$ KA) (7), which makes it then possible to increase output (torque = function of “Ampere x Turn”) with minimum loss while retaining the ultra-compact nature of the motor with ideally high energy efficiency. However, the problem still remains of creating a system for cooling the HTS motor to this level of LN_2/LH_2 temperature and maintaining such a temperature.

Meanwhile, in order to facilitate the spread of FC EVs and hydrogen engine vehicles, both of which utilize hydrogen resources, it is crucial that an infrastructure (i.e., hydrogen stations) be developed that are equivalent to gas stations for gasoline-powered vehicles. Given the present situation of the EU and North America, which currently hold the lead in this field, it seems that it would be most practical and feasible to use LH_2 tank trucks to deliver hydrogen produced off-site to such stations installed throughout the country, just as with gasoline. When it comes to generating hydrogen as a sustainable energy source, it has been pointed out that it will not be long before it becomes necessary to depend on hydrogen that is either generated off-site as a by-product or intensively produced using a new type of energy (primarily solar cell power) (7), (8). Whatever the case may be, it is likely that “LH_2 will be supplied to hydrogen stations.” If we consider this “LH_2 station infrastructure” in relation to the “use of HTS motors using LH_2,” we arrive at the concept of “LH_2 high-temperature superconducting hybrid electric vehicles (LH_2 HTS HEVs).” These completely clean, green, compact and energy-conserving vehicles that run on sustainable energy, namely, sun-generated hydrogen, and (liquid) hydrogen stations will surely guarantee to future generations the maintenance of a social system wherein these convenient and essential automobiles will play a core role.

By placing the spotlight on the development of infrastructure (LH$_2$ stations), as well as research efforts for higher efficiency LH$_2$ HTS motors, this report intends to establish "LH$_2$ vehicles," along with "high-pressure ambient temperature hydrogen gas vehicles," as additions to the development schedule for future hydrogen vehicles in Japan, out of a strong desire for early realization of a more ideal motorized society through integration with innovative HTS technology.

2. The past and future outlook of automobile technology

Figure 1 explicates the author's idea of "the past and future outlook of automobile technology (The road to the ultimate future car)," the reasons why such technology is necessary, and the innovative technologies that support it. The burgeoning population and economic lifestyle of the 20th century served to sharply increase the number of gasoline-powered vehicles, with the result that fossil fuel consumption and greenhouse gas (CO$_2$) emissions have increased rapidly. In order to address this urgent issue, an HEV using a combination of an electric motor and a gasoline engine was launched in 1997, which was also the year that the Kyoto Protocol was adopted (on December 10, 1997), as shown in **Fig. 2** (6). Subsequently, an EV that does not emit CO$_2$ yet offers higher energy efficiency has been developed, and it is due to hit the market this year (2009) as an qualified commercial vehicle. One of the most remarkable features of EVs is that they generate high torque at low speeds, while regenerating energy by converting the motor into a generator when brakes are applied. At the same time, HTS technology, which is distinguished by its "zero" electrical resistance, has shown rapid progress (1)-(3). An HTS motor using LN$_2$ cooled (77 K) HTS DI-BISCCO, rather than an electric motor using copper wire (used by forcibly water-cooling the heat generated as a result of current loss), was developed and tested on ships for the first time (4), (5), (12), the same year that the Kyoto Protocol came into effect on February 16, 2005, as shown in **Fig.2**. The HTS motor's compact size and high energy efficiency can be beneficial to all of the moving bodies listed in **Table 1**. At the Hokkaido Toyako Summit of 2008, Sumitomo Electric Industries, Ltd. exhibited and test-drove a prototype of the world's first HTS EV, details of which will be given below. Meanwhile, the peak-out and the depletion of fossil fuel resources and global warming with the increase in CO$_2$ emissions have become increasingly grave issues with the move into the 21st century (6)-(8). This has prompted governments and auto manufacturers around the world to develop and conduct a series of demonstration tests on FC EVs and hydrogen engine vehicles using H$_2$, which is considered to be the ultimate clean and green energy source (9), (10), (15), (19). At this point in time, however, efforts to develop such automobiles and the infrastructure necessary for them (hydrogen stations) are not necessarily being coordinated with each other, but are instead being carried out separately. What should be noted here is that Japanese manufacturers are all aiming to develop FC EVs using "high-pressure (300 to 750 atm) ambient temperature hydrogen gas," whereas BMW of Germany, for example, is seeking to develop hydrogen engine vehicles using LH$_2$. Likewise, many of the hydrogen stations in Europe and North America are designed to "supply hydrogen in both liquid and gas form (14)," whereas only "hydrogen gas" will be supplied at such stations in Japan to accommodate the needs of FC EVs. A cooling device must in principle be mounted within an LN$_2$-cooled HTS EV, which is a major disadvantage. However, if both automobiles and hydrogen stations use LH$_2$, HTS DI-BSCCO wire's Ic can be increased by a factor of approximately six (7) due to the fact that LH$_2$'s temperature is 20 K (-253 °C), thereby achieving greater compactness and higher efficiency in comparison with the use of LN$_2$ as a coolant and eliminating the

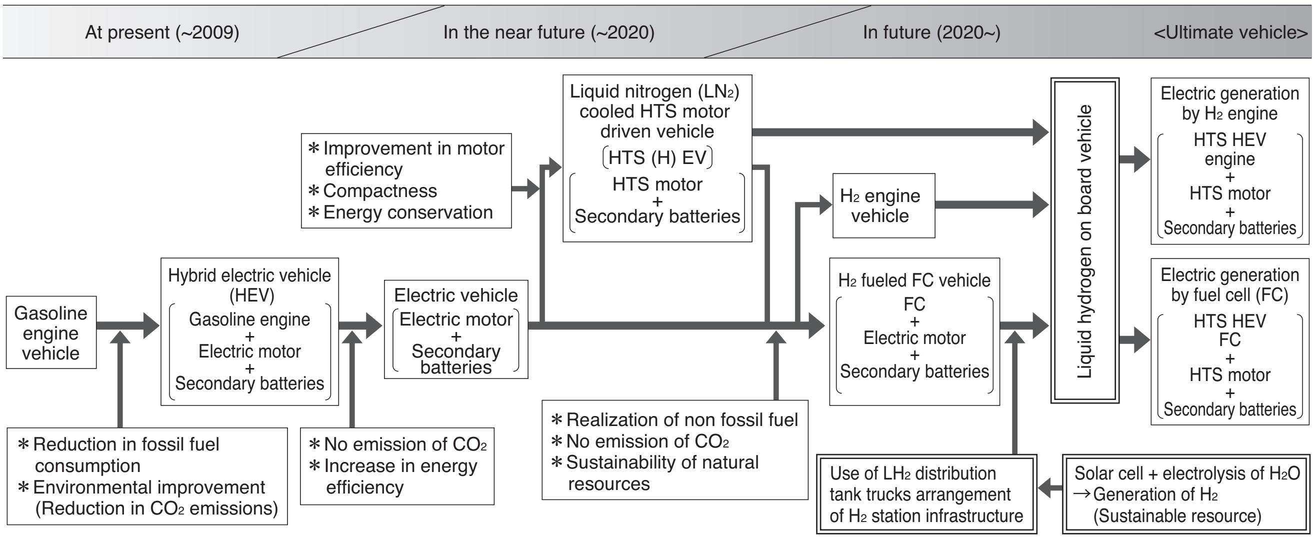


Fig. 1. Transition and future outlook of automobile technologies (The road to ultimate vehicle)

Table 1. Merits of HTS applications

Examples		Details	Low-loss	Compactness	Lightness	Big torque	High field	Preciseness	Silence	Maintenance	Stability	Total economy	Note
MRI (Medical use)		High field source	○	○	○		○			○	◎	○	Can be used in remote country
NMR		Extremely high field source	○				◎					○	Highest range (>1GHz)
Cable (AC, DC)		Large power transfer, low loss with small diameter	◎	◎							○	◎	American big PJ, collaboration with railway company
Transformer		For bullet train		○	◎								Utilizing its lightness
		For power transfer	◎	○								○	For underground substation
FCL		Fault current limitation	○								○	○	Higher reliability for existing grid
SMES		Energy storage	○				◎						For grid's stability
Vehicle	Maglev	Replacement of metal SC		○	◎					◎	◎	◎	Increase in stability, economy
	Ship propulsion	Reduction of drag force	◎	◎	◎	◎			◎	◎	◎	◎	AMSC, Japanese group
	Automobile	Weight saving using fuel cell	○	○	◎				○			◎	Air force
	Automobile	Big torque, low loss	◎	◎	◎	◎						◎	Liquid hydrogen is suitable
Solidification control		DC field for suppression, AC field for mixing	○				◎				○		Silicon crystal, steel continuous cast
Robot		Weight saving and preciseness		○	○	◎		○					Effective at the top of the arm
Mother machines		Extreme preciseness by D.D.			○	○		◎		◎			Free of gear wear-out
Magnetic separation		Medicine, waste	○				◎				○	○	Practical use in paper company
Wind generator		Weight saving of nacelle		○	◎	○			○			○	Lightness

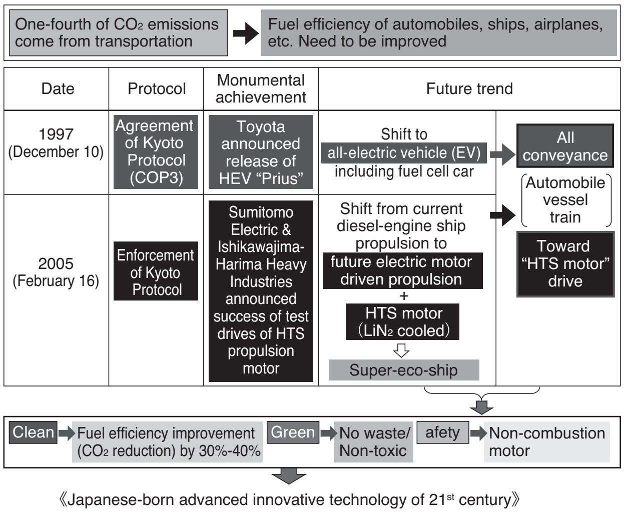


Fig. 2. Historical significance of HTS motor

need to mount a cooling device in the vehicle. In other words, the low temperature of the fuel (LH_2) may also be used to cool the HTS wire, resulting in the birth of an "ideal car" that overcomes the aforementioned disadvantages. Additionally, if H_2 is obtained as energy originating from the sun and delivered as LH_2 to hydrogen stations via LH_2 tank trucks, the path could be opened to maintain the sustainability of energy resources for driving automobiles and develop hydrogen stations as a form of social infrastructure. It is on these grounds that the author wishes to strongly urge Japan to not let European and North American countries take the lead in technological development but rather, in accordance with the roadmap shown in **Fig. 1**, aggressively seek to develop "LH_2 FC EVs or H_2 engine HEVs," in addition to "high-pressure H_2 gas FC EVs" as well.

3. The past and present state of the development of high-temperature superconducting technology

The 1986 discovery of the high-temperature superconducting phenomenon subsequently led to the discovery of various HTS materials, but the only commercial superconductor currently on the market is DI-BISCCO, which Sumitomo Electric developed from the first-generation superconductor BSCCO, and it comprises ceramics materials discovered in 1988 in Japan (1), (2), (17). That being said, Japan and the United States are currently engaged in competition for practical application and commercialization of the second-generation superconductor YBCO, which was discovered in the U.S. in 1987. When their efforts come to fruition, the industrial supply of HTS wire, which is more cost-competitive and offers higher performance than the first-generation superconductor BSCCO, will become possible. "High-temperature" superconduc-

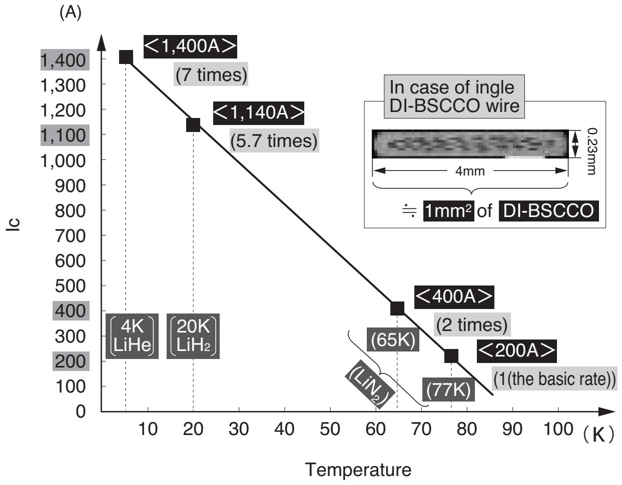


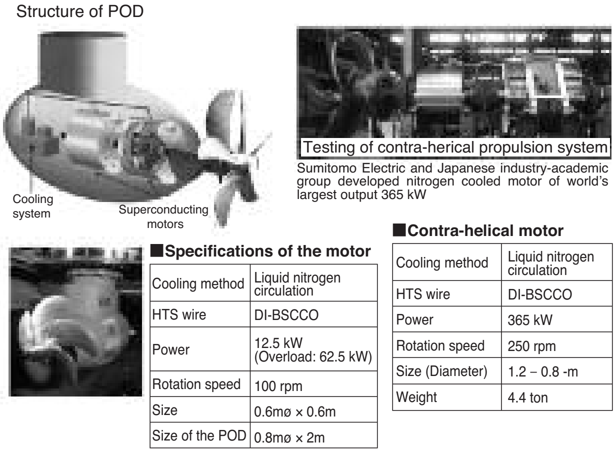
Fig. 3. Relationship between temperature and critical current (Ic)

tivity is so called because the material becomes superconducting at such a superconducting critical temperature (Tc) as above 77 K, the temperature at which liquid nitrogen is used as a coolant. With a nigh inexhaustible supply existing within the atmosphere, nitrogen (N_2) is easy to extract and liquefy, and thus is inexpensive (LN_2: approx. ¥50/L, mineral water: approx. ¥100/L), and possesses superior insulating characteristics. The permissible critical current (Ic) of these HTS materials is known to increase when they are supercooled. **Figure 3** shows how the coolant temperature relates to Ic. LN_2 is a superior coolant in that it is easily obtained and cooled, but it cannot serve as a fuel source. On the other hand, while LH_2 may not be easily cooled, it does offer some irreplaceable advantages. Once it has been liquefied its temperature drops to 20 K, allowing the HTS wire's Ic to increase to a level 5.7 times greater than that of LN_2 (7), and LH_2 itself is an excellent clean and green energy resource. Superconductivity is a phenomenon where electrical resistance is zero. For the purposes of industrial application, its high current, strong magnetic field, and ultra low loss (energy conservation) are taken advantage of. **Table 1** shows the potential applications of superconductivity. As each of these applications is successively realized, peripheral technologies will also progress and HTS wire will be mass-produced, with the result that its scope of application should expand (3), (16), (17). Because of its large current and low loss, HTS technology was first applied to a power cable (HTS AC Cable). In Albany, the state capital of New York, commercial electric power was transmitted to some 70,000 households in July 2006 through this cable for the first time in the world (13). In Japan, too, the Tokyo Electric Power Company is progressing the project to construct a demonstration cable at its Asahi Substation.

It is no exaggeration to say that HTS wire will be the key material that will lead innovative technologies in the 21st century, which has been dubbed as the "century of energy, resources, and the environment," the "era of hydrogen," and the "era of direct current." The author believes that leading the world in the development of HTS applied technologies is an important goal for Japan. So far, DI-BSCCO has achieved an Ic of greater than 200 A and line lengths of 1-2 km.

4. Development of HTS motors

Because of the need of high output at relatively low-speed rotation and high availability (the long continuous use of electric motors), a ship was chosen as the first subject for HTS motor application (4), (5), (12), that can meet part of the Super Eco-Ship (motor-driven contra-rotating propeller propulsion system) project of the Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT) and with economic considerations in mind, such as the large space available onboard due to the compactness of the HTS motor drive system. **Figure 4** illustrates the structure of a prototype HTS ship propulsion electric motor and a podded propulsor, which is believed to be the ultimate form of its application (16). While the United States Navy has announced its policy to install electric motor propellers in all of its vessels and craft, a 36.5 MW-



Sumitomo Electric and Japanese industry-academic group developed nitrogen cooled motor of world's largest output 365 kW

■Specifications of the motor

Cooling method	Liquid nitrogen circulation
HTS wire	DI-BSCCO
Power	12.5 kW (Overload: 62.5 kW)
Rotation speed	100 rpm
Size	0.6mø × 0.6m
Size of the POD	0.8mø × 2m

■Contra-helical motor

Cooling method	Liquid nitrogen circulation
HTS wire	DI-BSCCO
Power	365 kW
Rotation speed	250 rpm
Size (Diameter)	1.2 – 0.8 -m
Weight	4.4 ton

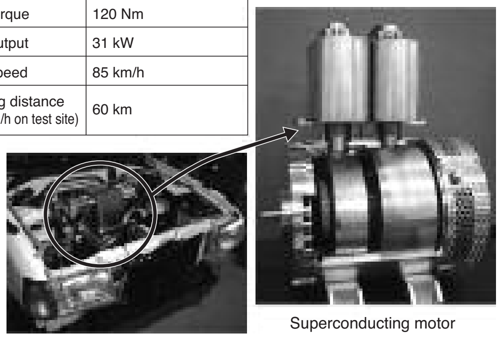
Fig. 4. HTS ship propulsion motor

Table 2. Merits derived form application of HTS motor to vehicles

Characteristics of HTS motor		Merits of vehicle with HTS motor
Merits over Engine	Quiet [against noise & vibration]	∗Distribution in early morning or at midnight ∗Home distribution vehicle; vehicles gathering to convenient stores
	High efficiency	Reduction of CO_2 emissions
Merits over normal conduction motor	Large torque for low speed	∗No need for transmission (Direct drive) ∗POD propulsion motor outside ships
	Compactness	∗Compact & light weight of vehicle's body → Low cost of fuel ∗More space for cabin

Superconducting electric car

Items	Performance
Cooling method	Liquid nitrogen immersion
Superconducting wire	DI-BSCCO
MAX torque	120 Nm
MAX output	31 kW
MAX speed	85 km/h
Cruising distance (at 30km/h on test site)	60 km



Superconducting motor

Fig. 5. World's first "HTS motor driven vehicle (HTS EV)"

class prototype HTS motor for their destroyers was test-manufactured and under trial run. Among the list of possible applications in **Table 1**, the use of HTS motors for EVs was chosen as a second priority application that allows the most to be made of their compactness and energy conservation (11). **Table 2** shows some of the general advantages of using HTS motors for vehicles. In order to determine the feasibility of this plan, Sumitomo Electric created a prototype HTS EV (**Fig. 5**) for exhibition at the Hokkaido Toyako Summit of June 2008, and successfully completed its test run. This particular model did not carry a cooling device but instead installed an HTS DC motor that is cooled with directly injected LN_2. The vehicle can run for several hours until the injected LN_2 evaporates. This prototype study and test run have both proved that HTS EVs are sufficiently feasible (11), (16).

5. Advantages and issues concerning HTS EVs

Of the vehicles currently under development, EVs, HEVs, FC HEVs, and PHEVs (Plug-in-HEVs) use electric motors and these electric motors can in principle be replaced with HTS motors. **Figure 6** shows a comparison of the basic mechanism of a copper-wire-wound normal conducting EV and an HTS motor EV, and the advantages of using an HTS motor. The followings are the advantages and issues concerning HTS EVs as illustrated in **Fig. 6**.

(1) In order to improve the performance of normal conducting motors, it is necessary to downsize the motor and increase the rpm to, for example, 10,000 rpm or higher in order to gain high torque. Since the motor's rpm is after all proportionate to the applied voltage, the motor's voltage needs to be increased. Thus far, motor voltage has been raised to approximately 500 V for HEVs, but this still requires the connection of a large number of vehicle batteries of approximately 1-3 V in series. In order to extend the life of rechargeable batteries, it is important to maintain an appropriate charge-discharge range. With multistage in-line, however, it is difficult to uniformly manage charge and discharge, and so a power management system becomes necessary. Even with such a system, the current HEV models require a voltage booster converter, or DC/DC converter, to be inserted between the motor and the batteries connected in series as given in **Fig. 6**, in order to obtain high applied voltage for the motor from the voltage generated by serially connected batteries, which ranges between 144 V and 288 V. Because of this, such a system requires the use of the followings.

(a) Serial many multistage rechargeable batteries
(b) Voltage booster DC/DC converter
(c) Many power semiconductors, which must be forced water-cooled
(d) Forced water-cooling of the motor itself

If an HTS motor is used, as indicated in **Fig. 6**, the number of turns (T) of the winding HTS coil can be reduced, as HTS wire's large current and low loss conduction make it possible to increase the current (A) (as in A·T <Ampere x Turn>) of a torque-generating motor, hence significantly lowering its voltage requirement. Because some tens of volts may be sufficient for LN_2-cooled HTS motors, the rechargeable batteries can be increased in capacity and then used mainly in parallel connection, uniform operation management of which is very simple. Also, it would no longer be necessary to use a voltage booster DC/DC converter or modify peripheral devices to resist high voltage.

(2) As described in (1) above, power semiconductors are frequently used. In order to increase forced water-cooling efficiency and achieve greater compactness (reduce the number of semiconductors used), however, current silicon-based semiconductors must be used at nearly the upper limit of their permissible tem-

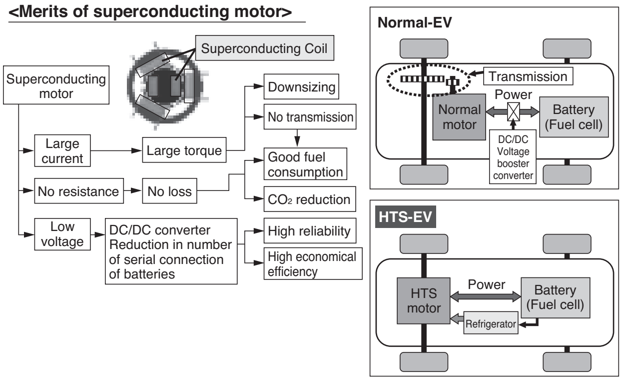


Fig. 6. Application of HTS motor to vehicle

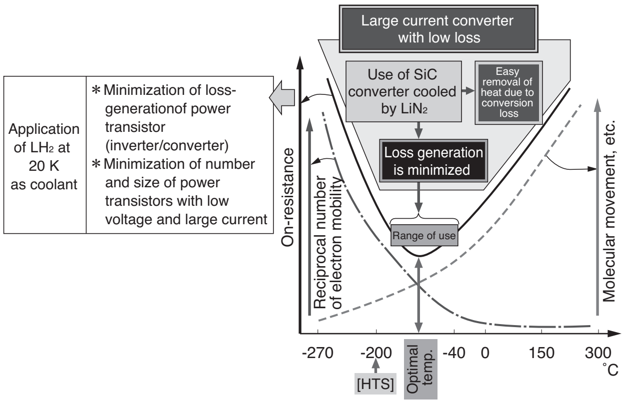


Fig. 7. Relation between on-resistance of power transistor and cooled temperature
- Use of SiC converter at very low temperature -

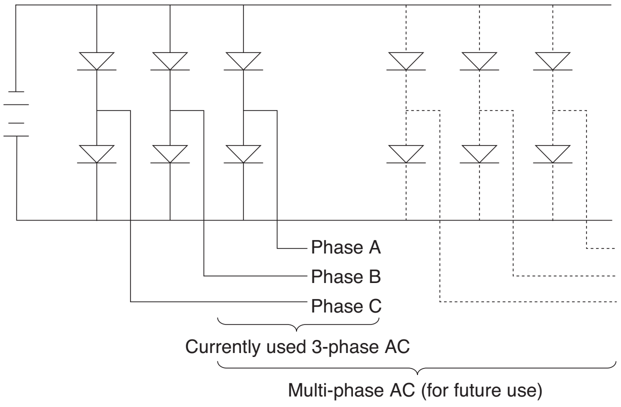


Fig. 8. Application of multiple phase alternating current (AC)

perature (over 100°C). With HTS EVs, a coolant of 77 K (LN_2) and 20 K (LH_2) may be used, and so the power semiconductors may be cooled powerfully using a coolant at very low temperatures. As **Fig. 7** clearly explains, the "ON resistance," which determines the loss of the power semiconductors, may be reduced significantly when used at very low temperature compared to the current use at high temperature environment. Since no electron can move at absolute zero (equivalent to infinite ON resistance), the optimal point of minus cooling temperature must exist (minimum ON resistance) (7). Preliminary research done by Sumitomo Electric has provided data suggesting that the minimum point is somewhere between -40 °C and -50 °C. Contrary to this, the data in reference (18) suggests that the minimum point lies somewhere between 40 K and 80 K (-233 °C and -193 °C), and that with LN_2 (77 K) ON resistance can be reduced to approximately one-seventh of that at ambient temperature. As just described, if the coolant cooling method for the HTS motor is applied to power semiconductors, the following advantages may be achieved.

(a) Significantly reduced loss generation
(b) Significantly increased throughput per power semiconductor, as the heat generated by large current can also be cooled largely (compact and simple)
(c) As LN_2 (as well as N_2 gas) works as good electric insulation, power semiconductors can be directly cooled with LN_2 or low temperature N_2 gas.

In addition, since the voltage applied to power semiconductors is also lowered as stated in (1) above, fabrication of the semiconductors themselves may becomes easier. Presumably, a completely new semiconductor design may be developed exclusively for such coolant cooled large-capacity power semiconductors for HTS motors. In order to prevent the amount of current required by a single power semiconductor to generate the necessary power level from becoming excessively large, one of the methods that may be adopted is to apply a multiphase electric power to an AC motor as illustrated in **Fig. 8**. If the "4, 5, 6… phase AC" is used instead of the current triphase AC, the required capacity for one power semiconductor may be reduced, thus making it easier to achieve "uniform current" for HTS coils (or, this may also be thought of as a method to increase the power of the HTS motor).

(3) In order to make the normal conducting motor currently in use for EVs smaller and more compact, the motor's rpm must be increased so that the necessary torque may be obtained. Because of this, a transmission is required to generate the slow speed and high torque necessary to drive a vehicle. However, a transmission can be rather bulky and complicated, and it generates an amount of loss when changing gears that is too great to be ignored (8% to 10%). Thanks to its large [A·T], an HTS motor can efficiently generate high torque at low speeds. Using an HTS motor can therefore eliminate the necessity of a transmission as described in **Fig. 6**, which is certainly a great advantage. This advantage was demonstrated by the prototype HTS EV exhibited at the Hokkaido Toyako Summit (See **Fig. 5**).

(4) An FC EV using H_2 as fuel can only generate approximately 0.8 V per cell at most. In order to obtain the applied voltage necessary for a normal conducting motor, several hundred cells must be serially connected. For instance, the "GM Hydrogen 4" uses an FC stack consisting of 440 series-connected cells (approximately 350 V, assuming 0.8 V/cell). For FC EVs, such multi-series (DC) cells require an advanced level of technology and strict management in terms of operation, reliability, service life, and maintenance (15). With an HTS motor that can run on LH_2 (20 K), the applied voltage required to drive the motor may be lowered. Be it rechargeable batteries or FCs, the parallel connection of a small number series is far simpler to operate than a multi-series connection. In addition to this, the technical requirements for increasing capacity (increasing the electrode area) to accommodate a parallel connection would instead be made easier, which then gives rise to the possibility of manufacturing economically efficient units for rechargeable batteries and FCs exclusively for EVs. This serves as a great source of the EVs' appeal.

(5) The coils of normal conducting motors are formed by

winding copper wire around magnetic materials. These magnetic materials exhibit a phenomenon known as magnetic saturation, i.e., a limit beyond which more torque cannot be gained regardless of the amount of additional current applied. Likewise, achieving low speed and high torque via a motor's high rpm and a transmission has practically its own limits. In the case of an HTS motor, on the other hand, because even an air-core coil can achieve large magnetic flux through large A in "A·T", there is no theoretical limit to "obtaining high torque." Should there be any limit under practical use conditions, it is still possible to realize a high torque motor for a vehicle, as its torque would be far greater than that generated by a normal conducting motor.

(6) In (1) - (5) above, the possibilities of HTS motors as being superior to normal conducting motors were discussed. The single most significant issue with EVs using an HTS motor is the question of how to generate and maintain an atmospheric temperature low enough to bring about the HTS state even in an EV. An HTS motor uses coolant in a thermally insulated closed system, but its temperature rises gradually due to the heat generated by the motor itself (this is truer for AC motors) and heat that leaks in from outside. Therefore it must be re-cooled no matter what, albeit intermittently. **Table 3** compares EVs both with and without a cooling device. As the table shows, the EV without a cooling device (into which liquid coolants <LN_2 / LH_2> are re-injected from outside when needed) renders a simple and easy solution for several applications that cannot be ignored, including operation base buses, construction machinery, and forklifts, which have limited times and places of use. On the other hand, a cooling device may be applied to any type of HTS EV, but this has its own drawbacks when it comes to the vehicle's energy efficiency: the cooling device must be in constant (intermittent) operation, regardless of the vehicle's state of use (even when it is parked). Because of this, as shown in **Tables 2 and 3**, the first batch of HTS EVs using LN_2 as a coolant—the technology expected to hit the market first—will be models with "high utilization" and "high transmission frequency," and which "require high starting torque." In more concrete terms, they will be used in buses, home delivery service vehicles, construction machinery, forklifts, and long-distance trucks, with the spread of the technology to passenger cars to follow. (Research has shown that the driving energy efficiency of an HTS bus with a cooling device is approximately 25% higher and 13% higher than that of an HEV bus and an EV bus using a normal conducting motor, respectively. However, the benefits of HTS EVs remain a subject for future investigation.)

Table 3. Low temperature generation and its maintenance

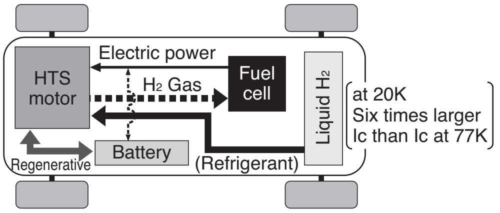
With refrigerator	Without refrigerator
Installation of refrigerator in vehicle & its constant (but intermittent) operation	Change of coolant-tank (or cartridge) (or refill of coolant like gasoline)
Applicable for all kinds of vehicles	＊Bus ＊Home distribution vehicle ＊Construction vehicles, forklift ＊Convoy truck
Immediate application: For vehicles with high rate of operation, frequent gear-changes and necessity of high starting torque	

6. LH_2-cooled HTS motors (The ultimate vehicles of the future)

In Chapters 1 and 2, the author explained the common view that, out of consideration for energy, resources, and the environment, vehicles using hydrogen as an energy source will become the automobile of the future.

In the item (6) of Chapter 5, on the other hand, the author pointed out that the necessity of an onboard cooling device would become a major issue for HTS EVs. The best solution to this issue is to develop "HTS EVs using LH_2 which serves both as coolant and fuel." If LH_2's cold energy stored in an LH_2 tank resistant to long-term storage could be used to cool the HTS motor, an onboard cooling device would be unnecessary and the advantages of the HTS motor (low temperature of 20 K; Ic approximately six times higher) could be obtained. **Figure 9** shows two possible systems for LH_2 EVs. Japanese manufacturers have yet to create a prototype LH_2 FC model of (A), but some overseas manufacturers, including GM, have made such a model [19]. No prototype model of (B), i.e., the LH_2 "series HEV" (hybrid EVs using fuel to run only an engine that drives the generator), has ever been made. As shown in **Fig. 10**, however, BMW has already developed "LH_2 on board and hydrogen engine vehicles," and has successfully performed test runs for a total of over 1.5 million km in Munich and other places. According to the company's website, BMW Hydrogen 7 uses a high-pressure hydrogen storage tank, thereby overcoming the problem of "boil-off (loss of LH_2 via evaporation)" and

(A)《Liquid hydrogen + Fuel cell + HTS motor》



(B)《Liquid hydrogen + Engine + HTS motor》

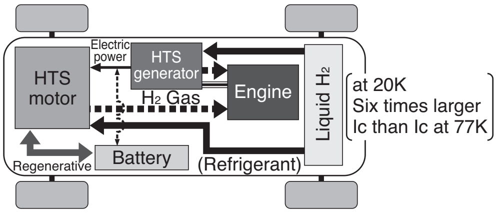
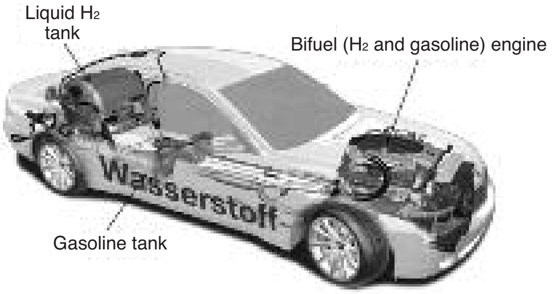


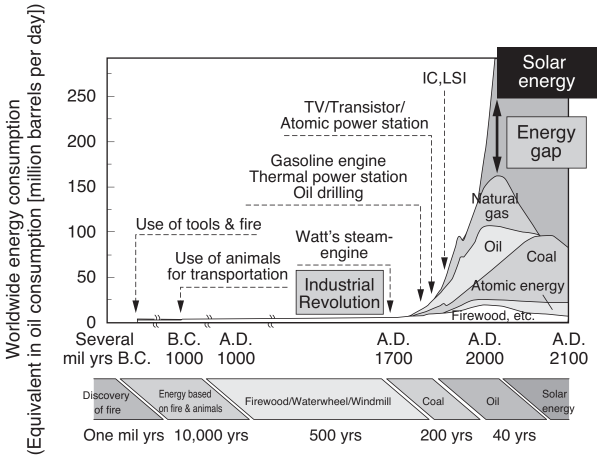
Fig. 9. HTS EV cooled by liquid hydrogen



Source: K. Yamane, BMW Japan Corp., "Data for Zero Emission Symposium 2007"

Fig. 10. Outline of BMW hydrogen 7

making it possible to store both LH_2 and high-pressure hydrogen gas in the tank. As shown in **Fig. 10**, when both LH_2 and gasoline tanks are used, the current prototype vehicle can run for over 400 miles (640 km). If only the LH_2 tank is used, however, it can run for 125 miles (200 km). At the same time, BMW suggests that using a 10-kg LH_2 storage tank, which the company is currently test-manufacturing, will allow over 350 miles (560 km) of distance to be covered. (The "weight" of the fuel has a bearing on this, but since H_2 is the lightest molecule, the "fuel energy weight density" for LH_2 is 2.7 times that of gasoline. Meanwhile, regarding the "energy bulk density," which is important because LH_2 is gasified before being combusted in the engine, the value of H_2 gas is one-fourth that of gasoline. When using hydrogen for vehicles, both of these efficiency indicators are taken into consideration.) It is believed that the existence of BMW's "LH_2 on board and hydrogen engine vehicle" will be an important step toward realizing the concept of "LH_2 on board and hydrogen engine HTS series HEVs," shown in **Fig. 9 (B)**.



Source: World Population Prospects 1990. Energy Statics Yearbook

Fig. 11. History & forecast of energy consumption by mankind

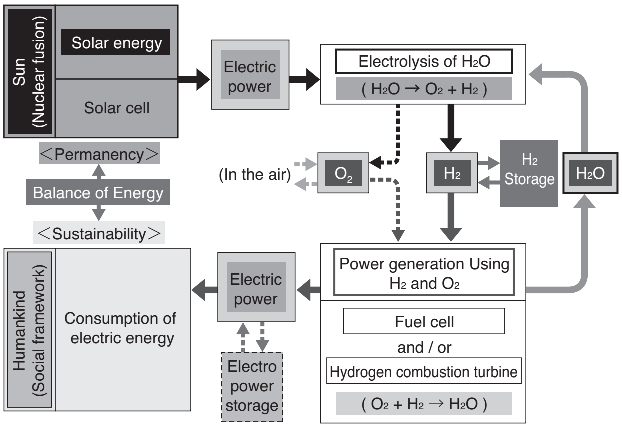


Fig. 12. Acquisition of solar energy through "water cycle"
- Permanent balance of energy -

7. Generation / transportation of LH_2 and "hydrogen stations"

Figure 11 illustrates how fossil energy resources, which are currently used as fuels for automobiles, will reach a peak and begin to decline, which was noted in Chapters 1 and 2 above. This figure clearly illustrates that, from a long-term perspective, humankind will be forced to opt for the efficient use of new sun-originated energies (7), (8).

Figure 12 shows how H_2 is generated (mainly by solar cells) and stored, and then recycled to create electric power. This is one of the most promising systems, because of the need to "store and use" a practical amount of sun-originated energy resources (8). As a means for transporting these two energy resources (LH_2 and electric power) from desert areas, in which solar power generation and storage facilities are expected to be mainly deployed, to areas of consumption, the construction of "LH_2 transportation pipes" has been proposed, inside of which HTS DC cables will be installed (20) (See **Fig. 13**). (Since the internal temperature of these "LH_2 transporting pipes" will be 20 K, HTS DC cables will be capable of transmitting large currents at low voltages.) If this proposal should become a reality, it will become possible to supply sun-originated, sustainable, clean, and green hydrogen and electric power to automobiles via "hydrogen stations" in areas of consumption in which HTS EVs are in use. **Figure 14** shows the present state of hydrogen stations (10), (19). From the viewpoint of sustainability of energy resources, the technique of obtaining H_2 by modifying fossil fuels on-site (at a hydrogen station) will not constitute a fundamental solution. Instead, a more practical and thus sustainable system would be one whereby H_2 generated off-site (specifically, the aforementioned sun-originated H_2) is transported to various hydrogen stations where it is then supplied to vehicles. Europe and the United States each have some sixty hydrogen stations either available or under construction (or planned). Many such stations supply both LH_2 and high-pressure H_2 gas. There are approximately ten LH_2 generating plants in the United States, and one or two in each EU member country. **Table 4** provides a comparison between LH_2 and high-pressure hydrogen gas. Judging from prior cases in Europe and the United States, when considering how hy-

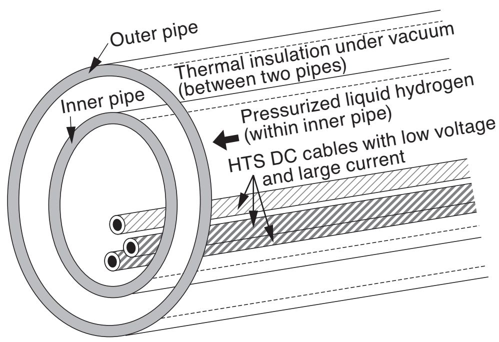


Fig. 13. Hybrid system of electricity transmission HTS DC cables in LH_2 delivering pipe

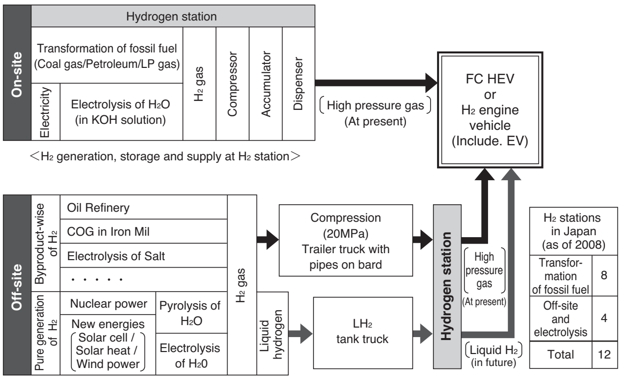


Fig. 14. Supply of H_2 to H_2 HEV through H_2 stations

drogen should be transported to the many hydrogen stations that would be constructed in the future, transportation of LH_2 by tank trucks is believed to be both superior and practical, as with the case of gasoline transportation via tank trucks. If we assume that "H_2's transportation (infrastructure) will be conducted by LH_2 tank trucks," the storage of hydrogen at each station in liquid form would be simpler in terms of capacity. If this is the case, as shown in the on-site diagram of **Fig. 14**, it would no longer be considered favorable to expend energy to gasify and pressurize hydrogen at stations in terms of energy efficiency, maneuverability, and operability in the field. **Figure 15** illustrates how "generation, storage, and transportation of hydrogen (and electric power) relate to 'hydrogen stations'" as based on the discussions above. In **Fig. 15**, both hydrogen and electric power are supplied to automobiles through a hydrogen station. The figure suggests that "high-pressure H_2 gas" may also be supplied, but it would be preferable to temporarily store LH_2 in that state at a hydrogen station and supply such LH_2 directly to automobiles. As explained thus far, when considering the entire process from generation of energy resources (off-site remote area) to final consumption, it would be most appropriate to supply LH_2 to future automobiles. If this is the case, an HTS electric motor capable of handling a large current at 20 K may be used, since the cold energy of LH_2

Table 4. Comparison between high-pressure H_2 gas and liquid H_2

	Items	Liquid H_2	High-pressure H_2 gas
Equipment	Refrigerator	Necessary	Unnecessary
	High-pressure pump	Unnecessary	Necessary
	High-pressure gas storage tank	Unnecessary	Necessary
	Coolant storage tank	Necessary	Unnecessary
Facilities (Convenience)	Storage density	○ (Large)	△ (Small)
	Delivery of H_2 fuel to H_2 stations	◎	×
	Easiness and safety of H_2 storage at H_2 station	○	△
	Easiness of taking on board	?	?
	H_2 carrying capacity & distance covered	○	△
	Risk rate in case of accident	○	△(?) [High pressure gas cylinder on board]
Function	Merits of application of HTS technique	◎ [Around sixfold critical current (Ic) compared with "In LN_2"]	×
Results	Non HTS	BMW's H_2 engine vehicle	FC (H)EV of Japan's automobile manufacturers, Toyota or Honda
	HTS	(For reference) Sumitomo Electric's trial vehicle of LN_2 HTS EV	—

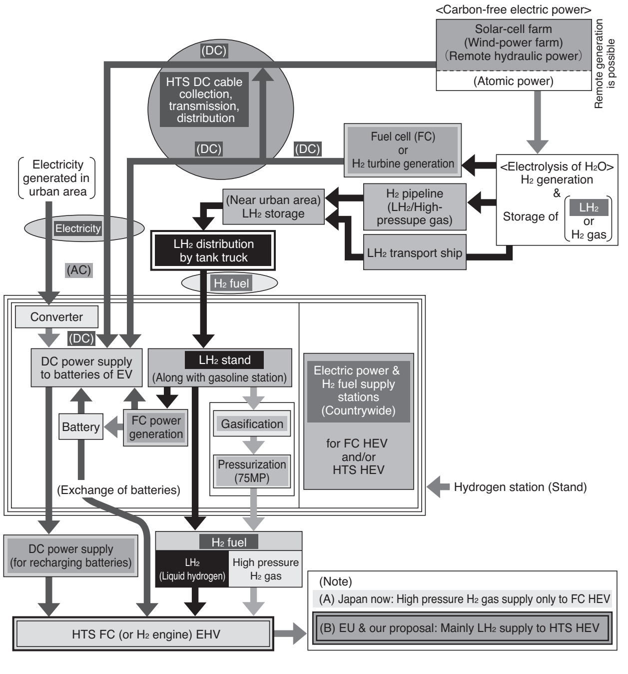


Fig. 15. Generation, storage & deliver of H_2 and electric power, and "H_2station"

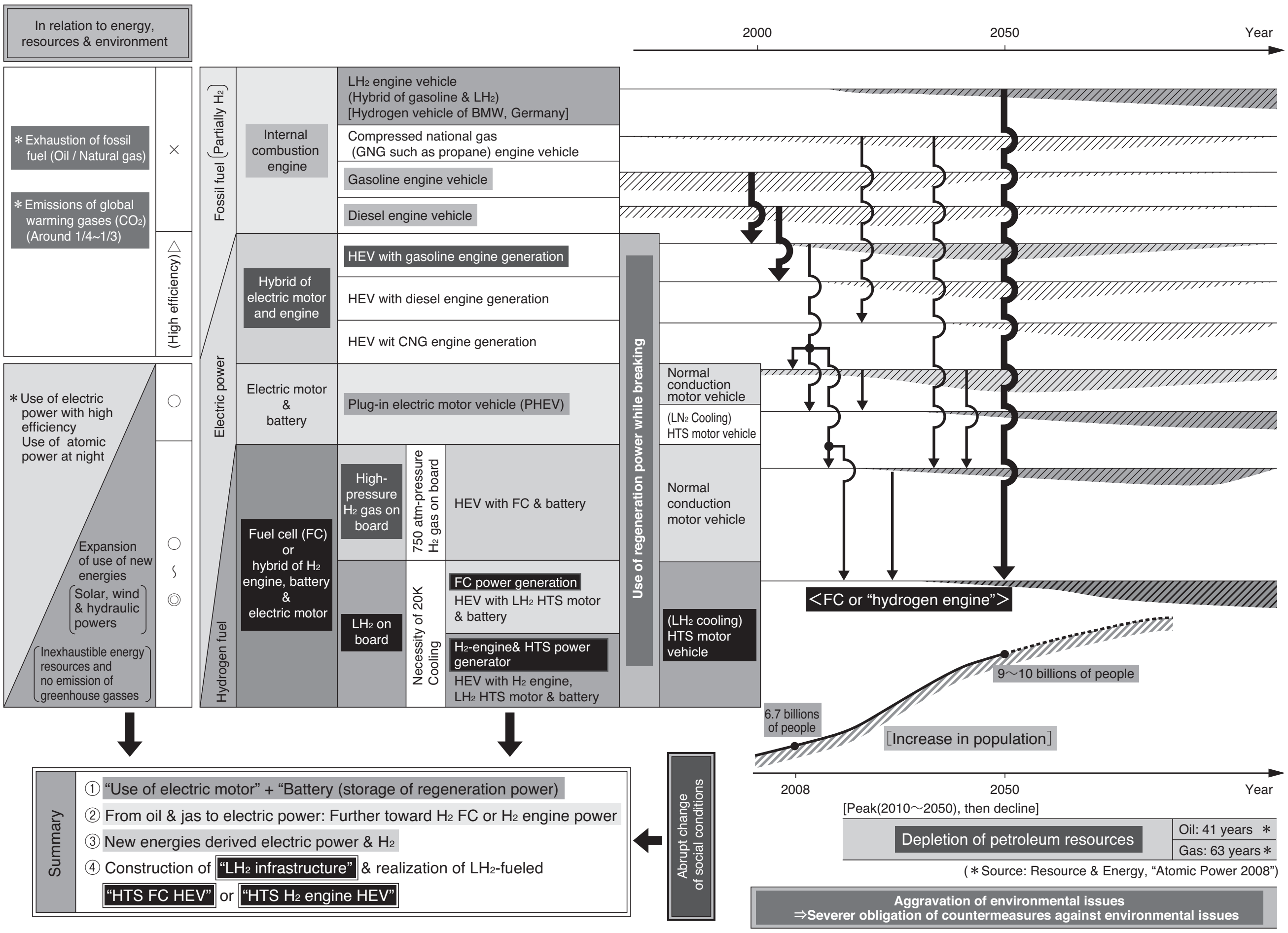


Fig. 16. The road to liquid hydrogen electric vehicle powered by high-temperature superconducting motor (LH₂ HTS FC HEV or LH₂ H₂-engine HTS series HEV)

can be used. Furthermore, it would also be unnecessary to mount cooling devices in cars, which is the single largest issue for HTS EVs. Either FCs or hydrogen engine generators may be used to generate electric power in a car using H₂. While FCs require innovative breakthroughs, such as elimination of the necessity of platinum catalysts, we can safely say that hydrogen engines are part of an already commoditized technology. Using a hydrogen engine to generate driving force, hydrogen vehicles do not use a generator (namely, a motor), and thus cannot use regenerative energy created while the brakes are applied. Thus, they are not preferable as far as energy efficiency is concerned. The author would therefore like to point out that LH₂ is the best alternative from the point of view of H₂ transportation infrastructures and that "LH₂ HTS HEVs" would be the ideal technology for automobiles running on LH₂ supplied at H₂ stations. Accordingly, the author believes that Japan should consider, research, develop, and commercialize "LH₂ HTS HEVs (including those using power generated by H₂ engines as well as FCs)," in addition to "high-pressure H₂ gas FC HEVs." (Here, H means the Hybrid in which FCs and rechargeable batteries are coused.)

8. Conclusion

Figure 16 sums up the essence of this paper, and outlines a roadmap leading from our present automobiles to the ideal automobile of the future, i.e., "LH₂ HTS HEVs (power for which is generated by FCs or a hydrogen engine)." As they are among the most convenient products of modern civilization, both the number and usage of automobiles will only increase as the global population expands and civilization develops in the coming centuries. It is quite natural that, from the standpoint of energy resources and environmental conservation, sustainable, clean, and green sun-originated hydrogen resources will become the mainstream fuels for automobiles. When we consider the development of an infrastructure involving the entire process from hydrogen generation to hydrogen stations, it is clear that LH₂ is obviously a more practical realistic choice than high-pressure H₂ gas. When we compare conventional automobiles that use only internal combustion engines and EVs (or HEVs) that may also use regenerative energy, the EVs' advantages in terms of energy efficiency should remain the same in the future. If we combine these two ongoing trends with HTS technology, which has made remarkable progress in recent years, an integrated system comprising an "HTS motor, battery, and converter," which does not require any onboard cooling device and thus is ideal for EVs, may be realized in the concrete form of "LH_2 HTS HEVs." The author wishes to point out that if we are to realize these "vehicles of the future" featuring innovative technologies (developed in Japan), it is of the utmost importance to alter Japan's current basic development policies that now only consider "high pressure H_2 gas," so as to also include "LH_2" within the scope of development.

* "DI-BSCCO" is a trademark or registered trademark of Sumitomo Electric Industries, Ltd.

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