ABSTRACT

Curbing emissions of carbon dioxide (CO₂), which is believed by many scientists to be a major contributor to global warming, is one of the top priority issues that must be addressed by automobile manufacturers. Automakers have set their own strategies to improve fuel economy and to reduce CO₂ emissions. Some of them include integrated approaches, focusing on not only improvement of vehicle technology, but also human factors (eco-driving support for drivers) and social and transportation factors (traffic management by intelligent transportation systems [ITS]). Among them, electric vehicles (EVs) will be a key contributor to attaining the challenging goal of CO₂ reduction. Mass deployment of EVs is required to achieve a zero-emission society. To accomplish that, new advanced technologies, new business schemes, and new partnerships are required.

This paper describes Nissan's challenges and solutions in the following three areas aimed at achieving widespread marketplace acceptance of electric vehicles:

- Technologies for electric vehicles, such as lithium-ion batteries and advanced motor control
- Establishment of an infrastructure with partners
- New business strategies based on the use of EV batteries, such as a battery leasing model and a new “4R” business model of reuse, resell, re-fabricate and recycle, to give EV batteries a second life as energy storage solutions in markets worldwide.

INTRODUCTION

Two of the most crucial issues that must be addressed by the global automotive industry in seeking to achieve sustainable mobility are to: improve the energy efficiency of vehicles and to reduce their CO₂ emissions. The Fourth Assessment Report [1] released by the Intergovernmental Panel on Climate Change (IPCC) in 2007 presents various scenarios for mitigating the increase in the global average atmospheric temperature that has occurred since the Industrial Revolution. According to one of the scenarios, the CO₂-equivalent concentration of greenhouse gases in the atmosphere must be stabilized at between 445 and 490 ppm in order to keep the temperature increase in a range of 2.0-2.4°C compared with the pre-industrial average. Accomplishing that will require a 50-85% reduction in greenhouse gas emissions attributed to global economic activities by 2050 from 2000 levels. This is equivalent to all new vehicles reducing CO₂ emissions by around 90% by 2050 from 2000 levels, based on Nissan's own estimation.

One measure for reducing CO₂ emissions from vehicles is to improve their energy efficiency. It is estimated that further improving the energy efficiency of internal combustion engines, including both gasoline and diesel variations, could potentially reduce CO₂ emissions by approximately 30% (Fig. 1). Hybrid systems that combine an internal combustion engine (ICE) and an electric drive motor could possibly reduce CO₂ emissions by approximately 50%. However, achieving even larger reductions in CO₂ emissions will require the use of alternative fuel vehicles such as electric vehicles or fuel cell vehicles. Electric vehicles do not produce vehicles any tailpipe CO₂ emissions while they are being driven, but thermal power plants that burn fossil fuels emit CO₂ in the process of generating electricity. Nonetheless, electric vehicles are expected to play an important role in the future as zero-emission vehicles because CO₂ emissions during power generation can be virtually eliminated in the
long term by implementing solar power generation and other forms of renewable electricity generation.

The World Energy Outlook 2009,[2] published by the International Energy Agency (IEA), predicts that the price of oil will continue to rise, as the balance between oil supply and demand will remain tight in the coming years. In this context, electric power is also significant with respect to energy security because it can be generated using many different types of primary energy sources such as coal, natural gas, nuclear power and renewable forms of energy.

This paper describes efforts that are being made to promote the introduction and acceptance of electric vehicles in the marketplace. One area being discussed is the development of technologies that will provide electric vehicles with sufficient performance to gain widespread consumer acceptance. Examples described here include high-performance lithium-ion batteries and advanced motor control technology. Another subject covered is the deployment of public EV charging stations and their associated infrastructure through partnerships with national and local government bodies and other organizations. Finally, the creation of new business strategies that make use of EV battery technology is also discussed.

DEVELOPMENT OF ELECTRIC VEHICLES

At Nissan Motor Company we have developed an all-electric vehicle called the LEAF, shown in Fig. 2, which is fitted with a high-performance lithium-ion battery. The LEAF seats five adults and provides a cruising range of over 160 km as measured under the LA4 driving cycle used in emission testing in the United States. Its drive motor produces maximum power of 80 kW and maximum torque of 280 Nm. The lithium-ion battery pack has a capacity of 24 kWh. The LEAF is equipped with two charging ports, one for normal charging and the other for quick charging. The charger shown in Fig. 2 is a 50-kW quick charging system. The LEAF will be put on the market in Japan and the United States in December 2010, and sales will also be launched in Europe early in 2011. Mass-market sales are scheduled to begin globally in 2012.

Among the various advanced technologies incorporated into the electric LEAF, the following will focus on three of them: the dedicated EV platform, laminated lithium-ion battery pack, and advanced motor control technology.

Instead of simply remodeling the platform of a gasoline-engine vehicle, a dedicated platform was specifically developed for the LEAF (Fig. 3). Designed with the mountability requirements of electrified components in mind, the platform gives the LEAF excellent body stiffness, aerodynamic characteristics and quietness. The platform concentrates the compact, high-performance powertrain (drive motor and inverter) at the front, while the battery pack, consisting of thin, laminated lithium-ion cells, is mounted under the floor. The addition of the members for securing the inverter and the frame for mounting the battery pack also simultaneously achieves high body stiffness. Aerodynamic characteristics have been substantially improved by the
smooth underfloor and the improvement of airflow around the fender mirrors. The adoption of this dedicated platform allows an optimum layout for the electrified components, enabling the LEAF to provide a spacious, comfortable interior along with quiet, spirited driving performance and high energy efficiency.

The next item described is the newly developed laminated lithium-ion battery pack. We began research and development work on lithium-ion batteries for vehicle application in 1992. Our activities included fundamental research on electrode materials, battery cell tests, and on-road testing of experimental vehicles. The experimental data accumulated through those activities went into the development of practical, high-performance batteries. [3] As shown in Fig. 4, the specific power of our lithium-ion batteries was markedly improved to 2.5 kW/kg and specific energy was notably increased to 140 Wh/kg. High battery reliability for vehicle applications were also achieved by changing the electrode materials and adopting a laminated cell structure. The manganese material applied to the positive electrode features a stable crystal structure that minimizes changes in the electrode shape induced by repeated charging and discharging. One issue of the previous cylindrically shaped cell was its large temperature distribution owing to a temperature rise at the center of the cell because of the limited area for heat radiation. A uniform temperature distribution was subsequently achieved by developing a cell with a laminated structure, which has greatly improved battery reliability under high-temperature operating conditions.

Figure 5 shows a comparison of vehicle acceleration performance from a standing start. The acceleration response of an electric vehicle to the driver's accelerator pedal input is markedly faster than that of an ICE vehicle. Because of the low torque output of an internal combustion engine at low speed, the torque must be augmented by the transmission. In contrast, the torque characteristics of an electric motor are optimally suited to an automotive powertrain because the motor can generate maximum torque even at low speed from a stopped state. The quick response from the moment of accelerator pedal input to the increase in motor torque enables an electric vehicle to deliver outstanding start-off acceleration performance. On the other hand, too fast a response can sometimes produce hunting in the motor torque. The original control technology that we developed suppresses torque hunting without sacrificing the excellent responsiveness of the motor, thereby securing smooth vehicle acceleration. This control technology provides a quick and highly responsive acceleration. By locating heavy objects such as a battery around the center of gravity of a vehicle (Fig. 6), yaw inertia becomes smaller than for an internal combustion engine vehicle, which translates to excellent handling and agility.

The third item concerns the motor and inverter. In addition to improving the torque characteristics and power conversion efficiency of the motor, an original control technology was developed that elicits the motor's full performance. The permanent magnet synchronous motor, capable of generating maximum power of 80 kW, is built with powerful magnetic materials enabling it to produce maximum torque of 280 Nm.
Besides increasing the specific energy of the lithium-ion battery and reducing aerodynamic drag by adopting the dedicated EV platform, various technologies were also developed for ensuring an acceptable cruising range. As illustrated in Fig. 7, the brakes and the motor operate in concert in the regenerative braking system to recover kinetic energy during vehicle deceleration. The braking forces of the mechanical and regenerative electric brakes are precisely controlled so as to achieve a natural braking feel combined with efficient energy recovery. Energy loss due to operation of the air-conditioner has also been minimized by developing a preset air-conditioning system, in addition to improving its operating efficiency. This system can be operated on electric power supplied from a battery charger while an electric vehicle is parked, thereby reducing parasitic energy consumption as much as possible during driving. Furthermore, innovative IT system driving support is essential in ensuring an acceptable cruising range. The vehicle is always-connected to a global data center, which provides updated cruising range based on battery energy consumption and driving conditions, and the display of charging points. This helps to ease customer anxiety over cruising range.

The development of the foregoing technologies enables the LEAF to provide outstanding acceleration and quiet, smooth driving performance, along with ample cruising range for everyday driving needs, and high reliability and durability. These performance attributes are intended to gain consumer acceptance of electric vehicles in the coming years.

DEPLOYMENT OF PUBLIC INFRASTRUCTURE

In order to promote the introduction of electric vehicles in the marketplace, the charging stations and other infrastructure facilities needed for supporting their use must be put in place along with advancing vehicle development activities. It is also important to adopt measures for enhancing the added value of electric vehicles.

With regard to charging facilities, it is envisioned that drivers will use ordinary chargers installed in their homes for routinely charging their EV batteries at night. Approximately 80% of everyday driving involves trips of less than 100 km. Accordingly, recharging EV batteries overnight at home will be sufficient for most everyday driving needs. However, as shown in Fig. 8, it will be necessary to put in place a public EV charging network to enable trips over longer distances. We are working on building a charging network consisting of both ordinary battery chargers and quick chargers. A quick charger using a three-phase 200-volt power source can recharge an electric vehicle battery in approximately 30 minutes. The task of building a charging network is not something that the automotive industry can accomplish alone. The work is being done in cooperation with national and local government bodies, electric utility companies and other partners.

One measure for enhancing the added value of electric vehicles is to make effective use of their batteries in the electric power grid. Renewable power generation systems are being implemented and expanded today as a way of reducing CO₂ emissions produced during electricity generation. The output of solar power plants and wind power plants is unstable, however, because it varies depending on the weather, among other factors. Implementing such power plants on a massive scale would require large-capacity storage battery systems in order to ensure a stable supply of electricity. [5]
It is conceivable that EV batteries could be used for the purpose of stabilizing the electric power grid by simply connecting them directly to the network for use as energy storage devices (Fig. 9). For example, the surplus electricity produced by solar power generation during the daytime, when a lot of power can be generated, could be stored in EV batteries. The stored electrical energy could then be discharged at night or during rainy weather, making it possible to use renewable power generation systems effectively. In other words, EV batteries could be used as grid-stabilization power-storage systems for renewable energy sources.

Drivers would not be able to use their electric vehicles, though, while the batteries were being used for the purpose of grid stabilization, nor could EV batteries be used for grid stabilization while the vehicles were being driven. However, the frequency of vehicle operating time is low. According to a study done by Axsen et al. [6] at UC Davis, vehicles are driven only about 6% of the time on average during one day. Approximately 90% of all vehicles are parked during the daytime when solar power generation is possible. Many electric vehicles could therefore be connected to the power grid during the day. Careful management of the battery state of charge of every parked electric vehicle could be expected to be effective in helping to stabilize the electric power supply and demand balance.

The following discussion concerns integrated approaches to the effective use of electric vehicles (Fig. 10). As another measure for using electrical energy more effectively, it is envisioned that EV batteries could be used as stationary...
energy storage systems following the end of their use on vehicles. After batteries have been used on electric vehicles and their performance has declined, they still retain sufficient performance to be used effectively in stationary applications. Connecting the batteries to the power grid would be helpful in stabilizing the power supply from renewable energy sources as well as in peak shaving for managing peak power demand.

Electric vehicles are not only on the demand side for receiving power during battery charging while parked at home or elsewhere, but they can also be on the supply side to provide electric power when it is needed. In other words, electric vehicles are not simply a means of mobility, they can also be used effectively as one element of the public electric power infrastructure.

Another project concerns the use of electric vehicles in optimizing transportation systems. The idea is to divide urban areas where traffic congestion is particularly severe into a city center zone and a surrounding zone, and to implement mobility systems suitable to each zone. Car-sharing, park & ride, and other systems could be put in place and more effectively integrated through the use of information and communication technologies. This would result in the deployment of next-generation mobility systems that are eco-friendly, highly convenient and very economical.

Concrete activities are already under way to use electric vehicles in promoting more effective use of electrical energy and in building next-generation mobility systems. Toward that end, we are forming partnerships with national and local government bodies, the electric utility industry and other organizations. Several specific examples of these activities are described below.

**Figure 10. Comprehensive roles of electric vehicles for energy storage, energy supply and mobility optimization**

In the smart house system, where EV batteries are connected to the power grid, surplus power produced by solar photovoltaic panels is used to charge the batteries. The batteries then discharge the stored electrical energy at night or at times of high demand in order to provide the required power. Since there is no need to suspend power generation by the solar photovoltaic panels, the system maximizes their usage rate. Moreover, the electric power produced by solar power generation can be used directly as energy for propelling electric vehicles.

Installing stationary storage batteries at EV charging stations that use solar power generation could maximize the usage rate of the solar photovoltaic panels. Nissan and Show Shell Sekiyu launched a joint project in 2009 to develop the electrical energy management technology for this type of system. The plan is to install solar power generation equipment at Show Shell Sekiyu's service stations along with a stationary power storage system based on the secondary use of EV batteries. A demonstration trial will be conducted to verify the utility of the solar-powered EV charging stations as emergency power sources and as quick charging facilities.

In 2010, the city government of Yokohama, Nissan and four other private-sector companies will launch the Yokohama Smart City Project (YSCP). Various activities will be undertaken in this project with the aim of enhancing local generation, electric power produced by solar photovoltaic panels during the daytime is used to meet the power demand of various types of electric equipment. Any surplus electricity is returned to the power grid. However, when the amount of power produced greatly exceeds the demand, the voltage of the electric power grid rises. As a result, the solar photovoltaic panels are disconnected from the power grid and their power generation function is suspended. This gives rise to the problem that the usage rate of the solar photovoltaic panels declines.

**Figure 11. Smart house concept for using EV batteries to stabilize solar power generation systems**
energy efficiency through new uses of EV batteries. This will also include verification testing of the smart house concept.

**Fig. 12. Smart community concept for using the batteries of parked EVs as energy storage devices for clean power generated by a mega-solar power plant**

Figure 12 outlines the “smart community” concept. This concept envisions clean power generation at a mega-solar power plant and the use of EV batteries as power storage devices while vehicles are parked. In order to manage the electric power grid of a smart community, it will be necessary to use information and communication technologies to gather information on many different fluctuating factors. These include the amount of electricity generated by the mega-solar power plant, the state of charge of the EV batteries and the power demand of households, offices and manufacturing plants, among other variables. That information will be used to control the charging and discharging operations of each battery. The development of the control technology is one of the objectives of the Yokohama Smart City Project. For this project, the plan is to build a 2.7-MW solar power plant and to put 2,000 electric vehicles into use. Nissan and General Electric also launched a joint research project in 2010 to study a power demand control system for households and buildings using the power storage capability of EV batteries.

It is envisioned that the expansion from smart houses to smart communities and then the networking of smart communities connected to power plants fueled by renewable energy sources will evolve into a smart grid (Fig. 13). Attempting to execute energy management for individual smart houses would have a limited effect on maximizing the usage rate of solar power generation. The reason is that power demand fluctuations would be too large owing to various fluctuating factors such as the amount of electricity generated and the operating conditions of electric vehicles. Expanding the scale to smart communities and further to the smart grid would allow greater flexibility for enhancing the benefits of total energy management. Increasing the usage rate of solar power generation will increase the proportion of low-carbon electric power and thereby reduce the amount of CO\textsubscript{2} emissions from vehicles.

**Fig. 13. Evolution of an optimized urban transportation system using electric power generation as a whole**

**Fig. 14. Secondary uses of used EV batteries**

Nissan and Sumitomo Corporation initiated a joint study in 2009 to examine potential secondary uses of EV batteries (Fig. 14). This study is examining energy storage solutions for global markets that involve activities to reuse, refabricate, recycle and resell EV batteries. Reuse refers to the secondary use of batteries as high energy density storage devices. Refabricate refers to disassembling battery packs and
repackaging batteries to meet diverse customer needs. Recycle means recovering raw materials from used batteries. Resell means selling batteries again for reuse as energy storage devices in applications apart from electric vehicles. These various activities for used EV batteries could be expected to help curb CO\textsubscript{2} emissions and also promote the acceptance of electric vehicles by reducing the cost to customers at the time of vehicle purchase.

A car-sharing strategy for electric vehicles is illustrated in Fig. 15 as one example of the use of electric vehicles to optimize urban transportation systems. People living in urban areas often use their vehicles for short trips, such as for commuting, shopping, hauling things and so on. A car-sharing program using electric vehicles is well-suited to such driving needs. Because electric vehicles emit no tailpipe pollutants, operate quietly and are easy to drive, they are ideal for use in congested urban areas. Moreover, a car-sharing program is suitable for urban areas where finding a parking spot can be difficult. It is envisioned that a user-friendly car-sharing program can be achieved through a control system that links electric vehicles to a data center at all times for easy management of vehicle operation. A study is now under way on an EV sharing system intended for deployment in urban areas.

The city of Yokohama and Nissan have launched a project to deploy vehicle-based transportation systems for a low-carbon society. Activities have already been initiated or are now being examined in four specific areas: 1. measures for promoting eco-driving, 2. verification testing of a route guidance system for mitigating traffic congestion, 3. measures for popularizing eco-friendly electric vehicles, and 4. evaluation of the effectiveness of the measures being examined along with dissemination of the resultant information. This project envisages the division of an urban area into a city center zone and an outer surrounding zone and the implementation of complementary transportation systems in each zone. For example, Intelligent Transportation Systems (ITS) technologies could be used to improve the efficiency of travel by conventional vehicles in the outer surrounding zone, while electric vehicles and personal mobility devices are used in the city center. Park & ride, car-sharing, and various other measures would also be implemented. The aim of this project is to reduce CO\textsubscript{2} emissions comprehensively by implementing different measures in the city center and in the surrounding area tailored to the mobility environment in each zone.

Finally, Fig. 16 shows the partnerships that Nissan has formed with various organizations around the world for the purpose of introducing and expanding the use of electric vehicles globally. As of June 2010, over 60 partnerships have been announced with national and local government bodies, companies and others in many different countries. Activities are moving toward the formation of still more cooperative relationships in the future. Efforts are steadily expanding globally to encourage the introduction of electric vehicles through the provision of subsidies and tax breaks, the construction of EV charging networks, and the establishment of dedicated traffic lanes and parking facilities, among other preferential measures. Electric vehicles are beginning to be put on the market in the United States, Europe, Japan and various other developed countries. It is expected that the expansion of these partnerships will work to accelerate the introduction and penetration of electric vehicles in markets around the world.

CONCLUSIONS

This paper has described the development of electric vehicle technologies and various measures for promoting their market introduction and widespread use. The principal points discussed are summarized below:

(1). The evolution of both lithium-ion battery and sophisticated motor control technology, and development of the dedicated EV platform, have enabled LEAF to provide an ample cruising range for everyday driving needs and
outstanding vehicle performance in areas such as start-up acceleration and handling, which exceeds the performance of internal combustion engine vehicles.

(2). In order to facilitate the penetration of EVs in the marketplace, it is necessary to develop a social infrastructure which serves to optimize the value of EVs along with making them more attractive. This includes:

a). Building and expanding EV charging networks

b). Expanding the generation of renewable energy and its smart use

c). Optimizing urban transportation systems with the effective use of EVs

It is essential to form partnerships with national and local government bodies and other organizations to realize the foregoing developments. Nissan has formed over 60 such partnerships worldwide as of the end of June 2010 in order to prepare for the proliferation of EVs, adjusted to the needs and conditions of each city.

(3). Studies have been launched concerning new business strategies for using EV batteries as social wealth. The need for electricity supply and demand management are increasing. As a result, verification testing of alternative energy strategies need to be examined. These strategies include the secondary uses of EV batteries as stationary power storage devices; the creation of smart houses/smart communities/smart grids; and, developing and using the charge-discharge technologies of EVs as electricity generators for the power grid when they are parked, which is usually over 90% of the day.

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CONTACT INFORMATION

Masanori Ueda
Planning and Advanced Engineering Development Division
Nissan Motor Co., Ltd.
1-1, Morinosatoaoyama, Atsugi-shi Kanagawa 243-0123, Japan
Phone +81-50-2029-0814
ueda@mail.nissan.co.jp

Toshio Hirota
Technology Planning Department
Planning and Advanced Engineering Development Division
Nissan Motor Co., Ltd.
1-1, Morinosatoaoyama, Atsugi-shi Kanagawa 243-0123, Japan
Phone +81-50-2029-0586
hirota@mail.nissan.co.jp

Atsushi Hatano
Technology Planning Department
Planning and Advanced Engineering Development Division
Nissan Motor Co., Ltd.
1-1, Morinosatoaoyama, Atsugi-shi Kanagawa 243-0123, Japan
Phone +81-50-2029-0595
a-hatano@mail.nissan.co.jp

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SAE Customer Service:
Tel: 877-606-7323 (inside USA and Canada)
Tel: 724-776-4970 (outside USA)
Fax: 724-776-0790
Email: CustomerService@sae.org
SAE Web Address: http://www.sae.org
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