1.Strategies for achieving net-zero CO_2 emissions by 2050※

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1. Introduction — Nissan Green Program 2030

1.1 Nissan's efforts towards sustainability

With sustainability forming the core of Nissan's business, systematic and strategic actions are being undertaken to realize the Nissan Ambition 2030 long-term vision and The Arc business plan. As part of this effort, a risk and opportunity assessment was conducted considering contemporary social issues, stakeholder interests, and the latest trends, such as technical innovations, to clarify the high-priority issues. This assessment identified 21 materiality items (critical issues) from environmental, societal, and governmental perspectives that should be addressed by the entire Nissan Group (Figure 1).

These issues were evaluated from the perspective of "impacts that society and the environment have on Nissan," which is the conventional concern for investors, as well as a new perspective, "impacts and value Nissan delivers to society and the environment." The 12 most important items exerting the largest impacts on either of these viewpoints were selected for prioritization.

These items are being incorporated into Nissan's business activities to establish an approach for building a sustainable company and, ultimately, a sustainable society. This approach will become a critical aspect of Nissan's business, and sustainability-related activities will be regularly promoted to realize a cleaner, safer, and more inclusive society.

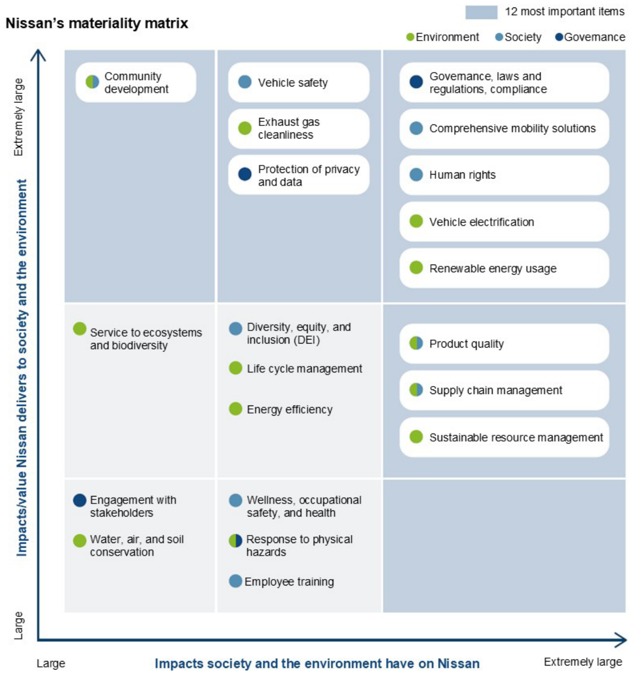

Figure. 1 Nissan's materiality matrix

1.2 Nissan's environmental activities — Nissan Green Program 2030

The environmental philosophy of realizing a "symbiosis of people, vehicles, and nature" was established at Nissan to promote the environmental aspects of our business and has inspired actions to realize the ultimate goal of "reducing the environmental dependence and load imposed by our business activities and cars to a level that nature can absorb, and passing on abundant natural assets to the next generation." Nissan's fifth mid-term environmental action plan, the Nissan Green Program (NGP) 2030, was announced in 2023 to promote the realization of a sustainable society that is in harmony with nature through the pursuit of activities that reduce environmental load and create positive environmental value.

Based on the materiality items identified for the entire Nissan Group, the most critical environmental aspects to be addressed by the NGP 2030 over the mid- to long-term comprise "Climate change," "Dependence on resources,"

※ This text is based on the data at the time of writing (October 2024).

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and "Air and water quality."

Company-wide activities addressing environmental issues will be accelerated in each of these areas. For example, activities in pursuit of achieving carbon neutrality to meet the 1.5°C target temperature increase, shifting towards a circular economy, minimizing dependence and impact on ecosystems, and strengthening business foundations will be promoted while creating new social values. Furthermore, conversations will be held with external stakeholders, including business partners, to understand their needs as they are asked to change their practices, helping to create a sustainable society together. Table 1 provides details of the key performance indicators identified by Nissan in NGP 2030.

Table 1 List of NGP 2030 key performance indicators

Issue	Area		2030 target	Environmental value	Related materiality
Climate change	Reducing CO_2 emissions (compared to 2018 levels)	Life cycle (t-CO_2/number of vehicles)	Global -30%	Contributes to carbon neutrality encompassing the entire vehicle life cycle through vehicle electrification and innovations in manufacturing processes	• Vehicle electrification • Renewable energy usage • Supply chain management • Community development • Sustainable resource management • Pursuing energy efficiency • Life cycle management • Response to physical hazards • Service to ecosystems and biodiversity
		Use of vehicles (g-CO_2/km)	Global -32.5% Four regions* -50%		
		Production (t-CO_2/number of vehicles)	Global -52%		
		Suppliers	Life cycle targets		
		Distribution			
		Research and development sites			
		Offices			
		Dealers			
Dependence on resources	Material resources	Increasing use of sustainable materials (mass basis)	Four regions* -40%	Promotes a circular economy by efficiently and sustainably utilizing resources and establishing a system that maximizes vehicle utilization	• Vehicle electrification • Renewable energy usage • Sustainable resource management • Supply chain management • Community development • Service to ecosystems and biodiversity
		Waste management / Landfill management	Maintain at low levels		
	Vehicle utilization	Expanding energy management function utilization	100% installation rate in EVs (Japan, United States, Europe)		
Air quality and water	Water	Strengthening water risk management at plants	Reduce the number of high-risk sites to zero	Minimizes impact on air quality by reducing emissions from vehicles and business activities; reduces water usage and promotes water quality management considering local issues	• Product quality • Supply chain management • Sustainable resource management • Exhaust gas cleanliness • Service to ecosystems and biodiversity • Water, air, and soil conservation • Response to physical hazards
		Reducing water usage at plants			
		Wastewater quality management at plants			
	Air quality	Reducing emissions from vehicles (including emissions other than from the tailpipe)	Develop and apply technologies		
		Volatile organic compound (VOC) management in plants	Continue activities (painting)		
		Managing vehicle interior air quality	Observe Nissan's standards regarding VOCs in the vehicle interior		
Foundation	Implementing responsible procurement practices		Manage supply chain risk	Identifies environmental risk within the entire value chain, provides accountability, and establishes a system for improving environmental performance	• Governance, laws and regulations, compliance • Supply chain management • Engagement with stakeholders
	Developing integrated management of value chain information and ensuring accountability (traceability)		• Establish and operate an information management system for data such as carbon footprints from business activities and parts production • Improve the reliability of supply chain information		
	Strengthening environmental governance				

* 4 regions: Japan, United States, Europe, China

2. Tackling climate change by 2030

The fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC), published in 2014, concluded that it is extremely likely that human activities are the cause of global warming.The twenty-first session of the Conference of the Parties (COP21), which was held in 2015, adopted a framework aiming to hold "the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels" (the Paris Agreement). This groundbreaking framework, which requires all participating developed and developing countries to pursue efforts to reduce carbon emissions, is a landmark for accelerating global activities to achieve decarbonization. Furthermore, the IPCC's sixth report stated that there is "no doubt" that emission of greenhouse gases by humans has warmed the planet, and COP26, held in 2021, adopted an ambitious resolution to "pursue efforts to limit the temperature increase to 1.5°C" (the Glasgow Climate Pact). Finally, following COP29 in 2024, countries agreed to raise at least 300 billion US dollars annually by 2035 (increased from the former 100 billion US dollars) to help developing countries fight climate change. Concrete progress was also made in setting goals and establishing systems for adapting to climate change by reducing greenhouse gas emissions, including the determination of detailed rules for international cooperation to reduce and remove greenhouse gases (such as carbon markets, as described in Article 6 of the Paris Agreement).

In 2021, Nissan aligned its efforts with strong global trends promoting adaptation to climate change by setting the goal to achieve carbon neutrality through the entire product life cycle, including all business activities, by 2050. (Figure 2)

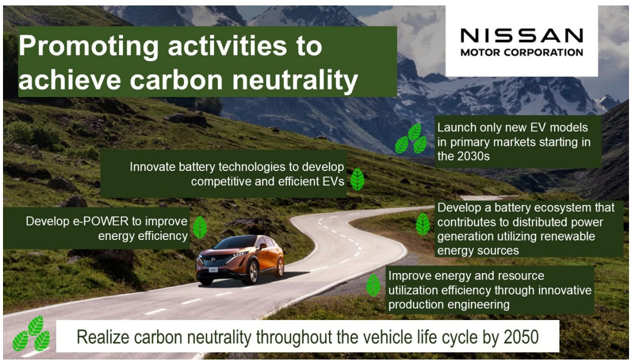

Figure. 2 Setting the goal to achieve carbon neutrality by 2050

In the climate change section of the NGP 2030 report, the CO_2 emissions target to be achieved by 2030 was specified as a major milestone towards realizing Nissan's 2050 goals. (Figure 3)

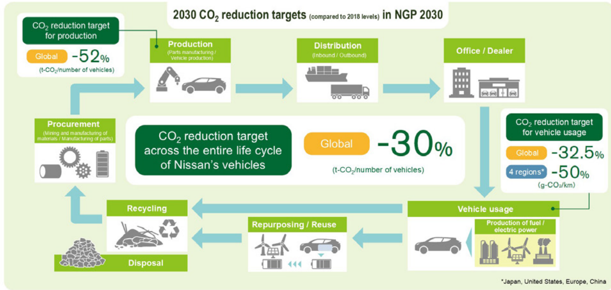

Figure. 3 CO_2 targets in NGP 2030

Nissan intends to achieve a 30% reduction in its CO_2 emissions through global efforts across the entire vehicle life cycle, from procurement to production, distribution, offices, sales dealers, and vehicle usage by 2030 (compared to 2018 levels). Furthermore, within the vehicle life cycle, Nissan intends to conform to the 1.5°C scenario for CO_2 emissions reductions from in-house production (which should be borne by the vehicle manufacturer) as well as vehicle usage.

To meet these goals, the per vehicle CO_2 emissions from in-house production at global production sites must be reduced by 52% by 2030 (compared to 2018 levels). This goal will be achieved by minimizing energy consumption, electrifying facilities that are powered by fossil fuels, and changing to carbon-free energy sources.

Furthermore, the CO_2 emissions from vehicle usage must be reduced by 32.5% globally and 50% in the four main regions served by Nissan (Japan, the United States, Europe, and China) by 2030 (compared to 2018 levels). In 2023, when Nissan vehicles were predominantly equipped with internal combustion engines, CO_2 emissions during vehicle usage accounted for approximately 80% of emissions produced during the entire life cycle. The Arc business plan sets the goal of expanding the lineup of electric vehicles (EVs) to effectively reduce CO_2 emissions over the vehicle life cycle by launching 34 EV models in the market from FY2024 to FY2030, covering all segments. This goal is consistent with the anticipated model mix of EVs in the global market, which is expected to reach 60% by FY2030. (Figure 4)

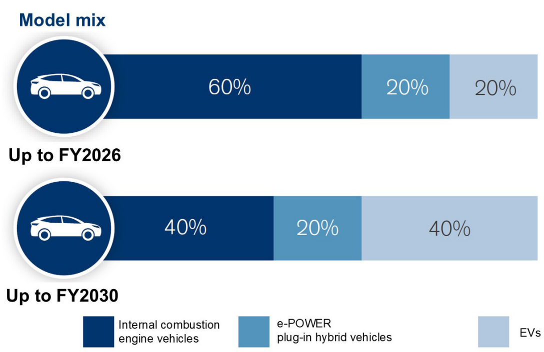

Figure. 4 Plan for the electrification of Nissan vehicles as defined in The Arc business plan

These continuous and proactive activities and information disclosures led CDP, an international non-profit organization in the environmental field, to award Nissan an “A” certification in the climate change area in FY2024. Indeed, Nissan has received leadership-level “A” or “A-” certification for 12 years in a row, from FY2013 to FY2024. Notably, Nissan received two “A” certifications in FY2024, one for climate change and another for water security. Clearly, a third party has recognized Nissan’s environmental activities.

3. Tackling climate change by 2050

As discussed in Section 1, Nissan has set the long-term goal of achieving carbon neutrality by 2050 (Figure 2). Figure 5 shows the approach adopted to achieve this goal, which comprises promoting electrification, reducing CO_2 emissions from manufacturing processes, developing an EV energy ecosystem, implementing a circular economy, and embracing CO_2 removal and other future technologies, as detailed in Table 2.

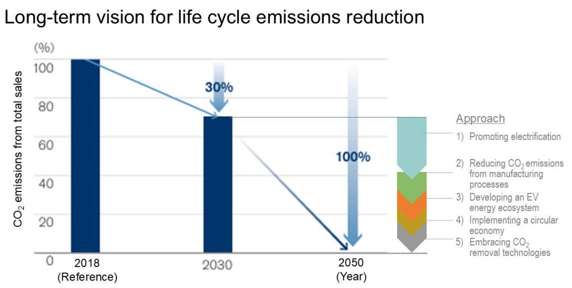

Figure. 5 Long-term vision for realizing a zero-emissions life cycle

1) Promoting electrification

First, the widespread use of battery-driven EVs must be facilitated by improving basic performance. For example, technological development is required to make the cost of an EV equivalent to that of an internal combustion engine vehicle to expand EV utilization.

In addition, the value of EVs must be maximized in a variety of scenarios to ensure that they are accepted and used by Nissan customers. Indeed, not only do EVs provide an excellent driving experience zero tailpipe emissions, they can also perform many secondary functions, such as supplying electric power during natural disasters and proactively charging from electricity generated by solar power facilities. Nissan’s Blue Switch electrification initiative, which promotes these functions, has been developed to resolve social and local issues associated with electrification in an attempt to “Make Japan even more beautiful with blue” and will be promoted with our partners. Together, these activities aim to expand EV sales, reduce CO_2 emissions, and realize a sustainable society.

2) Reducing CO_2 emissions from manufacturing processes

The CO_2 emissions from manufacturing processes will be reduced by completely electrifying any plant equipment that is currently driven by power sources such as gas or steam. Simultaneously, the electricity used to power this equipment will be obtained from fully renewable sources, including in-house fuel cells utilizing alternative fuels, to realize carbon neutrality in production plants.

These changes will be implemented first, as they can effectively utilize existing automotive production capacity. However, carbon neutrality cannot be achieved by solely reducing the CO_2 emitted by these activities.

3) Developing an EV energy ecosystem

Renewable energy EV charging must be proactively promoted, and vehicle-to-everything technologies and systems must be developed to enable the use of renewable energy for driving as well as in homes, offices, manufacturing sites, and other applications.

4) Implementing a circular economy

Implementing a circular economy requires developing technologies that enable effective reuse, recycling, repurposing, and refurbishing to minimize the CO_2 emissions throughout the entire product life cycle. In the case of EVs, life cycle CO_2 emissions can be minimized through the development and promotion of battery reuse and recycling technologies.

5) Embracing CO_2 removal and other technologies

Finally, promising future technologies for the removal of CO_2 from the atmosphere, such as direct air capture, will be identified and applied to sequester residual CO_2 emissions and contribute to the realization of carbon neutrality.

Table 2 Scope of activities for achieving carbon neutrality and examples

Activity	Approach	Details
Manufacturing next-generation EVs	1) Promoting electrification	Improving EV competitiveness using all-solid-state batteries
		Expanding EV value by utilizing them in activities that contribute to local communities (Blue Switch)
	2) Reducing CO_2 emissions from manufacturing processes	Applying processes that emit less CO_2 (e.g., solid oxide fuel cells)
		Developing EV36Zero
Integrating next-generation EVs into society	3) Developing an EV energy ecosystem	Developing vehicle-to-grid technologies
	4) Implementing a circular economy	Commercializing battery reuse
		Applying regeneration processes with low costs and low CO_2 emissions (e.g., direct cathode recycling)
	5) Embracing CO_2 removal and other technologies	Deploying direct air capture or similar technologies

Technological developments for 1) promoting electrification and 2) reducing CO_2 emissions from manufacturing processes are steadily progressing as they are within the scope of the automotive sector’s primary business. However, efforts towards 3) developing an EV energy ecosystem, 4) implementing a circular economy, and 5) embracing CO_2 removal and other technologies will require ongoing cooperation with entities outside the automotive sector.

Indeed, Nissan's steady implementation of measures to manufacture next-generation EVs as a member of the automotive sector must proceed alongside efforts to strengthen connections with stakeholders in the supply and value chains, broaden cooperation, and implement technological developments. By describing our goals, progress, and issues through transparent communication, Nissan hopes to strengthen this cooperative framework. As a part of such efforts, this special feature explains specific activities undertaken by Nissan in pursuit of our emissions reduction and carbon neutrality goals.

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2. Improving the competitiveness of EVs using all-solid-state batteries

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1. Introduction

The intention to launch electric vehicles (EVs) with internally developed all-solid-state batteries by 2028 was announced in the Nissan Ambition 2030 long-term vision[1]. All-solid-state batteries (ASSBs) comprise a broad class of energy storage technologies that include solid polyelectrolyte or quasi-solid systems that partially contain electrolyte solutions. An ASSB employing an inorganic solid electrolyte that is ideal for ion conduction is currently under development at Nissan. This type of battery replaces the liquid (organic solvent) electrolyte used in conventional lithium-ion batteries with an inorganic solid electrolyte. The high physical/electrochemical stability and ideal ion conductivity of inorganic solid electrolytes can be applied to realize both higher energy density and improved charge/discharge performance, which have not been realized simultaneously in the past.

In addition, obtaining battery material resources is increasingly difficult owing to the widespread adoption of EVs. Therefore, securing mineral resources at stable prices represents a critical issue in the automotive industry. In contrast to the limited number of organic electrolyte solutions used in conventional lithium-ion batteries, inorganic solid electrolytes are expected to employ a wider range of battery materials from electrochemical and physical perspectives, enabling the adoption of materials with high capacities, low costs, and stable supplies. Examples of potential materials include sulfur cathodes, which are prone to the dissolution of reaction intermediates as well as the shuttle effect in organic electrolyte solutions, and manganese, which also reacts with organic electrolyte solutions and dissolves in the system. Therefore, ASSBs represent an innovative technology that can accelerate the widespread use of EVs through their excellent characteristics as well as their potentially reduced cost.

This article describes the performance improvements realized in the ASSBs being developed by Nissan through advances in both materials and processes and describes the future prospects for ASSBs.

2. Solid electrolytes

Research on inorganic solid electrolytes (SEs) has a long history that can be traced back to the 1970s, when solid-state ionics were incipient. At that time, research was primarily focused on silver- and copper-ion inorganic SEs (e.g., AgI and $Rb_4Cu_{16}I_7Cl_{13}$) as these metals are stable and exhibit high ion conductivities[2][3]. Research on lithium-ion conductors progressed rapidly in the following years owing to the promise of lithium-based batteries, whereas difficulties associated with processing and joining the interfaces between inorganic materials limited reports on practical ASSB characteristics until research by Kondo et al.[4] and Takada et al.[5] was published in 1992 and 1996, respectively. This research was conducted on sodium super ionic conductor type electrolytes and reported on the charging/discharging properties of an ASSB using Li_3PO_4-Li_2S-SiS_2, which increased attention on sulfide SEs[4][5]. Subsequently, systematic research on Li_2S-P_2S_5 glass ceramics was undertaken by Minami et al.[6], and investigations of Li_2S-GeS_2-P_2S_5-based thio-lithium super ionic conductor SEs were conducted by Kanno et al.[7] Indeed, the $Li_{10}GeP_2S_{12}$ (LGPS) SE proposed in 2011[7] was shown to exceed the conductivity of liquid lithium-ion electrolyte solutions. The research and development of lithium-ion ASSBs subsequently accelerated. In recent years, SEs exhibiting ion conductivities two to three times higher than those of liquid electrolytes have been reported, primarily owing to improvements in argyrodite-type (Li_6PS_5Cl) or LGPS-type electrolytes[8]. Notably, the use of a sulfide-based SE has been shown to provide excellent pressure-molding properties at room temperature and facilitate relatively easy increases in battery size. Therefore, sulfide-based SEs are considered promising candidates for next-generation large-capacity vehicle-mounted batteries (Figure 1). However, various challenges must be addressed before their practical application. In particular, battery materials, electrode structures, and fabrication processes must be developed to form and maintain stable contact surfaces (interfaces) between the electrolyte and electrodes, which is virtually ensured when using a liquid electrolyte. Nissan's work

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toward forming such stable interfaces is described in the subsequent sections of this article.

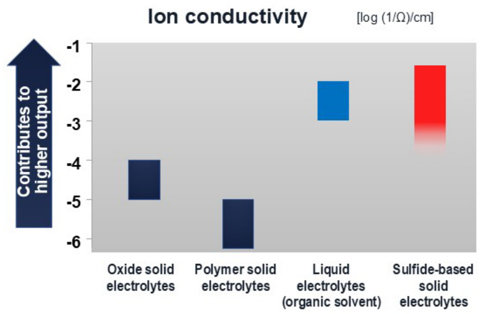

Fig. 1 Ion conductivities of various electrolytes

3. Interface design at the cathode

The cathode in a conventional lithium-ion battery using a liquid electrolyte typically exhibits a three-dimensional porous structure formed by cathode active material (CAM) particles such as ternary systems comprising lithium nickel–manganese–cobalt oxide, conductive additives such as carbon, and binders such as polymer resins. During the battery manufacturing process, the interface between the CAM and electrolyte is formed by first creating the cathode structure and then injecting the liquid electrolyte using a process called electrolyte wetting. In contrast, the electrolytes used in ASSBs comprise solid particles that must be mixed with the CAM, conductive additives, and binders in advance such that they are evenly dispersed throughout the battery. As a result, point contacts exist between the SE (providing the ion pathway) and CAM (acting as the ion storage element), in contrast to the solid–liquid contact in liquid electrolyte batteries. Therefore, the critical decision during ASSB design is how to uniformly disperse the particles to increase the number of contact points while securing the necessary ion pathways.

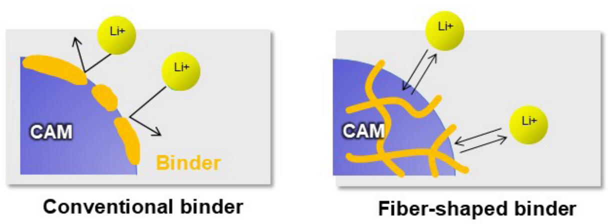

Fig. 2 Securing ion pathways by altering the binder structure

The effects of binder material type on the structure of the interface at the cathode are illustrated in Figure 2. A conventional binder exhibits a glue-like amorphous coating structure that covers a large portion of the CAM surface to bind adjacent particles. In this structure, the number of contact points between the CAM and SE particles will be insufficient, resulting in high battery resistance.

In contrast, a binder comprising fiber-shaped structures forms a three-dimensional mesh that enables multiple particles to be structurally bound without requiring the binder to cover the entire surface area of the CAM. In this structure, the number of contact points between the CAM and SE particles can be increased to reduce resistance while maintaining the desired material strength (Figure 3).

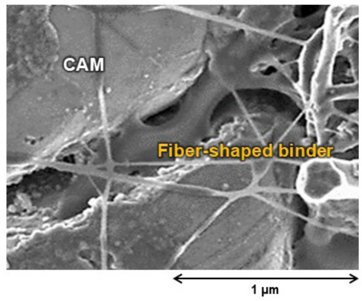

Fig. 3 Scanning electron microscope image of the surface of an active cathode material coated with a fiber-shaped binder

Notably, battery resistance can be minimized by uniformly dispersing the constituent materials (CAM, SE, and conductive additives) before fixing the electrode structure using the fiber-shaped binder. Therefore, material dispersion is considered to be the most critical process in ASSB fabrication.

The creation of electrode structures using different dispersion methods, as well as binarized cross-sectional scanning electron microscope (SEM) images of the actual electrodes, are shown in Figure 4. The electrode produced using the conventional process, which did not provide sufficient mixing, included large agglomerations of electrolyte particles that resulted in tortuous ion conduction pathways, limiting ion conduction in the direction of the electrode thickness. As a result, a concentration gradient was formed, leading to a high battery resistance. In contrast, the electrode created using an improved mixing process that suppressed electrolyte particle agglomeration formed relatively straight ion conduction pathways that lowered the battery resistance to one-tenth that of the battery produced using the conventional mixing process. Although the effective dispersion provided by the mixing process is a critical consideration, few tests have been developed to quantify the level of dispersion resulting from a process utilizing micrometer-scale particles of different sizes and shapes. Therefore, the formation of the electrode structure was modeled using particle simulations to analyze how the particle shape, state of agglomeration, and dispersion method affect the level of electrolyte dispersion in the electrode[9]. The number of SE particles in each agglomerate, which was assumed to control dispersibility, was varied to investigate the effects on the electrode compression characteristics and structure. These simulations were based on the discrete element method, considering interparticle collision, rotation, and friction. Particle contact was simulated using the Hertz–Mindlin and Johnson–Kendall–Roberts models, and the interparticle force between agglomerated particles was specified to provide a binding force that was removed when a specified stress was applied, causing the agglomerated particles to separate.

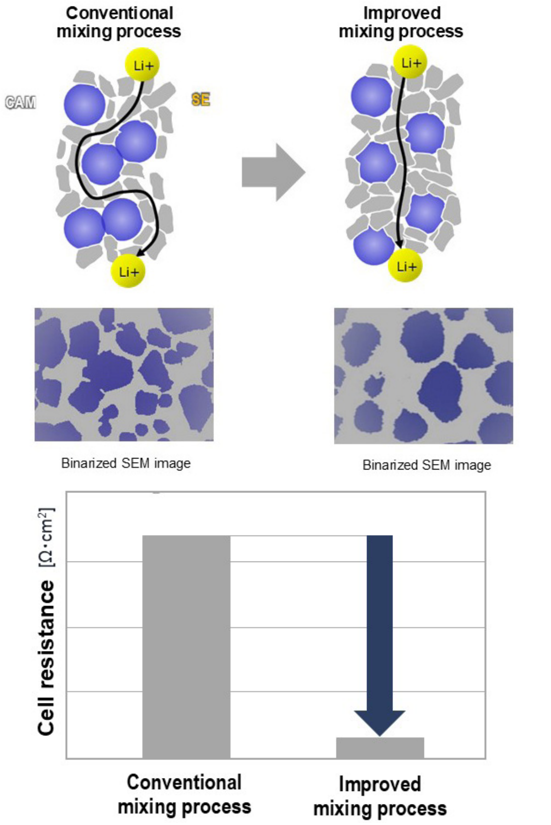

Fig. 4 Comparison of the structures and performances of electrodes obtained using different dispersion processes

The CAM particles and agglomerated SE particles were initially arranged randomly within the space established inside the periodic boundaries, as shown in Figure 5(a). Next, the mixture was packed by gravity, as shown in Figure 5(b), and then further compressed using a flat plate to form the electrode structure, as shown in Figure 5(c). Finally, the density and linearity of the ion pathways formed by the SE particles in the obtained structure were analyzed.

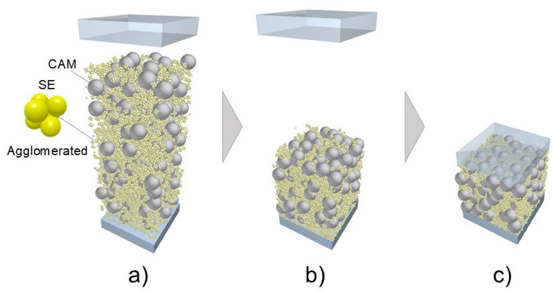

Fig. 5 Particle simulation process

Figure 6 compares the relationships between the pressure applied during compression and the electrode material relative density according to the number of SE particles in each agglomerate. The material density clearly decreased from the early stage as the number of agglomerated particles increased and remained low even after compression was applied. Notably, a low material density can be expected to decrease the effective ion conductivity of the composite electrode[10], indicating a potential decline in cell performance. Specifically, the density decreased by approximately 3% when the number of SE particles in each agglomerate increased from 1 to 6, indicating that the effective suppression of SE particle agglomeration is critical.

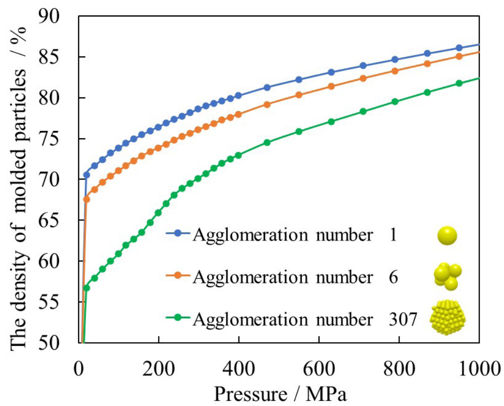

Fig. 6 Relationship between the number of SE particles in each agglomerate and material density

4. Interface design at anode

The SE layer in an ASSB, which is formed by densely molding the SE material, is used to electronically insulate the cathode from the anode. Lithium-ion batteries typically employ porous separators that cannot prevent short-circuiting via dendrite precipitation formation; as a result, metallic lithium, which theoretically possesses the highest energy density among available materials, cannot be used as the anode in such batteries. In contrast, the physical strength and density of the SE in an ASSB prevents dendrite precipitation and thereby permits the use of metallic lithium. In addition, although organic electrolyte solutions reductively decompose against metallic lithium, some SEs are electrochemically stable against this material, suggesting that any increase in resistance owing to reductive decomposition and film formation should be extremely small. However, if a flat-shaped type electrode (such as metallic lithium) is used in an ASSB, the contact interface at the SE (reaction interface) will be a two-dimensional plane (in contrast to the three-dimensional contact among dispersed particles in the cathode), increasing the reaction current per unit electrode interface area (current density). From an engineering perspective, even a slight contact failure under these conditions can cause considerable irregularities in the reaction current (reaction distribution), potentially facilitating the generation and growth of lithium dendrites at the anode during the charging process. Therefore, maintaining an appropriate contact state at the anode–SE layer interface is critical for ensuring rapid charging performance.

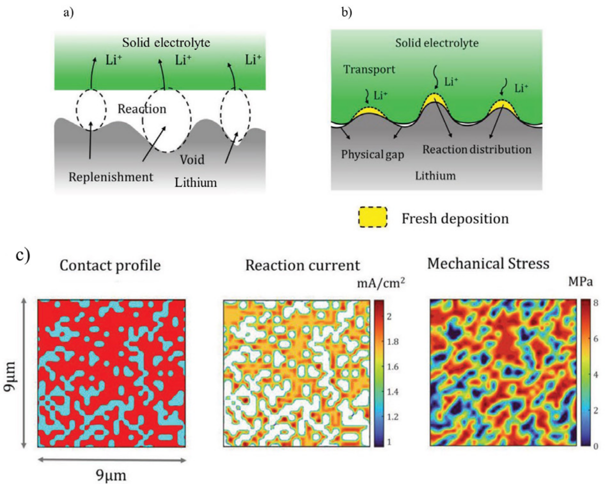

Fig. 7 Schematic diagram of the anode–electrolyte interface a) Void formation when Li dissolves; b) Contact restoration when Li precipitates; c) Contact, reaction, and stress distributions at the interface according to roughness

The effects of the external constraint pressure on the state of contact at the anode–SE layer interface were investigated using microscopic and macroscopic evaluations. On the microscopic level, the influence of the micrometer-scale roughness at the interface on the reaction distribution was investigated using model simulations because evaluating this unevenness through tests and observations is extremely difficult[11]. A schematic of the employed model is provided in Figure 7, in which the SE layer domain (green) is shown above the anode metal lithium domain (gray).

The following process was used to simulate the reaction distribution: (1) an interface with a randomly generated roughness profile was provided, and the contact distribution at this interface was calculated under a constant external constraint pressure; (2) the surface pressure distribution was calculated from the obtained contact distribution (Figure 7 c); (3) the obtained contact and surface pressure distributions were applied to calculate the deformation of the metallic lithium anode in the lamination direction and its dissolution owing to electrochemical reactions per time interval; (4) the obtained deformation and dissolution of the metallic lithium anode were compared for each calculated area of the segmented interface, with conditions in which the degree of deformation exceeded that of dissolution defined as maintaining interface contact and conditions in which the degree of dissolution exceeded that of deformation defined as no contact; (5) the contact distribution of the entire interface after an a single time step was calculated and applied to repeat the calculations described in steps (2) to (4) to determine the contact area fraction at an arbitrary reaction time.

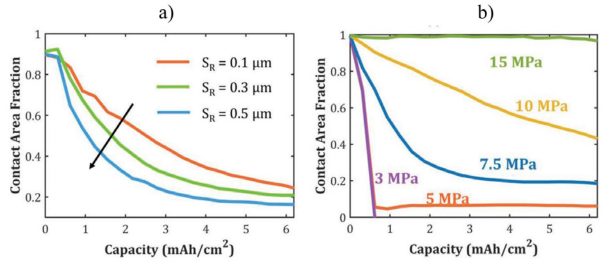

Fig. 8 Temporal change of the interface contact area fraction a) Roughness sensitivity; b) External constraint pressure sensitivity

Figure 8 shows example results indicating that the anode–SE layer interface contact area fraction decreased as discharge progressed when the interface roughness was higher or the external constraint pressure was lower. Thus, the smoothness of the interface between the SE layer and metallic lithium anode, as well as the external constraint pressure, are critical parameters for ensuring the stable operation of this ASSB.

On the macroscopic level, the influences of the external constraint pressure and temperature distributions likely to occur in a vehicle-mounted environment were investigated using similar simulations. An external constraint pressure must be applied to an ASSB to create a stable solid–solid interface between the SE layer and anode. However, applying a completely uniform constraint pressure over the large area typical of a vehicle-mounted cell can be quite difficult. Therefore, some degree of uneven contact pressure distribution can be expected to occur when the cell is mounted in a vehicle. In addition, an uneven temperature distribution can occur within the cell, especially during high-output charging or discharging, similar to conventional lithium-ion batteries. Both these parameters will affect the reaction distribution in an ASSB. Notably, when a metallic lithium anode is used, these factors may determine the displacement of lithium precipitation. Therefore, in addition to the microscopic material distributions, the influence of the macroscopic constraint pressure and temperature distributions on cell performance must be considered when designing an ASSB system for a vehicle-mounted environment.

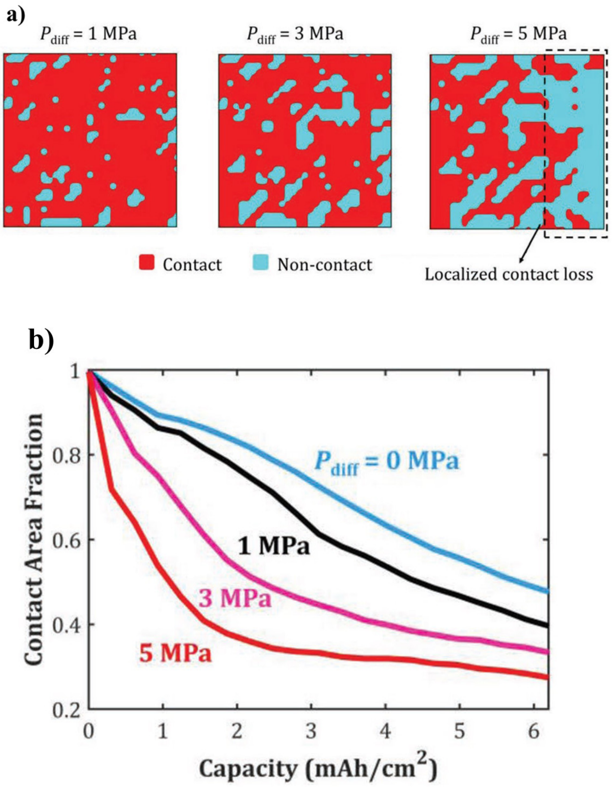

Fig. 9 Influence of surface pressure distribution on the interface contact area
a) Interface contact area fraction after discharging under different surface pressure distribution conditions;
b) Dependence of interface contact area maintenance fraction on surface pressure difference

Figure 9 shows the results of calculations conducted using the microscopic model, in which the change in the interface contact area during discharge is shown under constraint pressure gradients of 1, 3, and 5 MPa applied in the flat surface direction. As shown in Figure 9 a, the contact area maintenance fraction of the metallic lithium anode–SE layer interface decreased as discharge was performed under increasing constraint pressure gradients. The maintenance of the anode–SE layer contact interface during discharge depends on the balance between the local reaction distribution governed by microscopic unevenness (i.e., the quantity and distribution of Li dissolution) and the anode creep deformation compensating for such distribution. As the macroscopic distribution of stress induced in the metallic lithium anode by the external constraint pressure represents the determining factor for anode creep speed, it exerts a significant influence on this balance.

5. Conclusion

The key to improving the performance and the practical application of ASSBs is "forming and maintaining a stable interface," and this must be realized by considering not only the materials but also the electrode forming processes (such as mixing and dispersion) and the packaging of the battery as a device, whose characteristic is represented by the constraint pressure. Furthermore, it is most important that safety as a product is verified. However, since there are almost no ASSBs available on the market, there is still very little data related to their safety. Therefore, a designing method and safety evaluation method also need to be established. Since 2010, after the successful launch of the world's first mass-produced EV "LEAF," Nissan has gained experience on developing EVs and vehicle-mounted lithium-ion batteries and thus accumulated vast knowledge on safe and reliable design. By utilizing this knowledge to the maximum extent, we will accelerate development towards the practical application of ASSBs in the near future.

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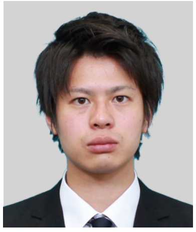

Hiroki Kawakami

3. Expanding values of EVs by utilizing them to solve social issues (Blue Switch)

Yuichiro Takahashi*　Noriko Ishida*　Nakako Gondo*

1. Introduction

The most distinctive characteristics of electric vehicles (EVs) compared to that of gasoline vehicles is that they emit zero tailpipe emissions while traveling and can supply electricity. Based on these characteristics of EVs, the "Blue Switch" project (Figure 1), which aims at electrifying Japan to tackle social issues by utilizing EVs, was announced by Nissan in May 2018. "Blue Switch" represents the resolution and mission of Nissan, the pioneer of EVs, to realize a zero-emission society and implement measures for social innovations by promoting the widespread use of EVs.

EVs can contribute to securing electricity, and therefore, achieving a more widespread use of EVs is expected to contribute to realizing decarbonization and strengthening resilience during emergencies. Energy management that is completely free of CO_2 emissions can be realized if renewable energy is combined with EVs, which would also enable reusing EV batteries. Further, there are many possible methods for utilizing EVs, including sustainable tourism and solving transportation issues.

Utilizing EVs with the above-mentioned characteristics is steadily gaining momentum across the country. As of October 2024, six years after the start of the Blue Switch project, partnerships have been signed with approximately 270 local governments, companies, and other organizations to implement measures for accelerating the decarbonization movement, strengthening the resilience of local communities, and realizing a sustainable society.

This article introduces the activities of the electrify Japan "Blue Switch" project and some specific case examples of utilizing EVs to solve social issues.

Fig. 1 Blue Switch Project

2. Decarbonization

In October 2020, the Japanese government announced that it would aim to reach carbon neutrality by 2050 by reducing overall greenhouse gas (GHG) emissions to zero. Since then, activities to achieve decarbonization have accelerated. From the total CO_2 emissions in Japan, approximately 18% are attributed to the transportation sector, and approximately 88% of these emissions to automobiles. Therefore, the electrification of vehicles is essential for realizing carbon neutrality(1). To address this scenario, a goal has been established to reach 100% electrified vehicles (including EVs) for the new vehicle sales by 2035, and various measures have been implemented for achieving that goal. For example, subsidies from the country or local government can be received when purchasing EVs. Although EVs are considered expensive, they can receive eco-car tax breaks that serve as tax incentives. Further, when purchasing a new vehicle, it is possible to receive subsidies (up to 850 thousand yen) from the country to purchase next-generation vehicles with excellent environmental and energy performances. In addition, this aids in accelerating the development of innovative batteries and increasing the number of electricity-charging bases.

The total CO_2 emissions from EVs, including the entire life cycle from production, distribution, usage, and scrapping assessed via life-cycle assessment indicates that the total emissions by the Nissan LEAF 40 kWh were 32% lower compared to that of gasoline vehicles of the same class (Figure 2). In the power-generation mix of

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Japan, a certain amount of electricity is generated using fossil fuels. In the current scenario, EVs emit more CO_2 when electricity generation is considered; however, CO_2 emissions that account for electricity generation will decrease when the ratio of renewable energy in the power generation mix increases in the future, thereby making it possible to further increase the CO_2 emission reduction effect in the LCA of EVs.

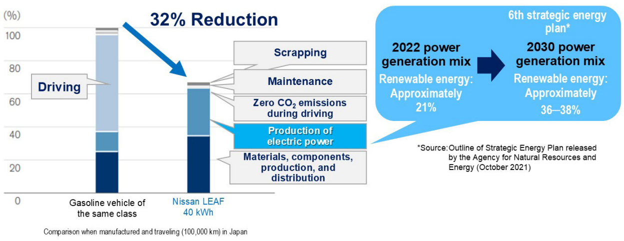

Fig. 2 Comparison of CO_2 emissions encompassing the entire vehicle life cycle between gasoline vehicles and EVs

In line with the increasing momentum to achieve a decarbonized society, there has been a steady increase in the number of local governments and companies that adopt EVs as their official or company vehicles because EVs emit less CO_2 than gasoline vehicles.

3. Resilience

Japan has experienced many natural disasters because of its geography, landform, weather, and other natural conditions. In recent years, large typhoons and strong rainfall have occurred almost annually. In this scenario, enhancing and strengthening disaster prevention measures are important tasks for local governments.

The basic concept of disaster cooperation between local governments and the Nissan Group (including its dealers across the country) is that local governments introduce EVs for use as official vehicles during normal times and utilize them as emergency power supplies when power outages occur. Through its dealer, Nissan, which is located within the relevant local government, lends its EVs to the local government. Therefore, the local government can secure the maximum number of emergency power supplies.

Some local governments have also asked residents for cooperation. Local residents and companies that own next-generation vehicles capable of supplying electricity are asked to register as volunteers beforehand so that their vehicles can be lent out to shelters or other locations to cooperate in supplying electricity when power outages occur after safety is confirmed. An increase in one EV indicates that one unit of emergency power supply has increased. Faced with repeated natural disasters, an increasing number of local governments are attempted to introduce similar systems.

Some examples of Nissan's natural disaster assistance activities in which its EVs are utilized are presented below. In the case of the Typhoon Faxai (typhoon No. 15), which occurred in September 2019 and caused prolonged power outages in Chiba Prefecture, the Nissan LEAF made significant contributions as an emergency power supply. The day after the typhoon caused extensive damage, some Nissan employees heard the news that the power outage may continue for a long time. The employees gathered volunteer drivers and drove the Nissan LEAF to cities such as Ichihara, Kisarazu, and Kimizu, which suffered from large-scale power outages. The geographical scenario was advantageous as these cities were close to the Yokohama Headquarters when the Aqua-Line was used, and therefore, there was sufficient electric power remaining in the vehicles after arriving at the cities.

After arriving at the community centers and city halls, it took some time for Nissan's employees to explain that electricity could be supplied from EVs because many city employees had no such knowledge. However, it is very easy to supply electricity from EVs, which enabled the city employees to quickly understand the operation method after listening to the explanations. After driving the Nissan LEAF to the affected cities, the vehicles were used to charge smartphones. However, after the city employees realized the usefulness of the vehicles, they asked Nissan employees to supply electricity to more people. Consequently, LEAF made even more contributions by supplying electricity to places where there were many vulnerable evacuees, such as elderly care facilities and nursery schools. The supplied electricity was used for powering electric fans, cooling water in refrigerators, etc. because not using electricity during hot seasons can cause fatalities. In another city, where the self-defense force established a water station, it was so dark during the night that the local residents could not locate the water station. Therefore, the Nissan LEAF was driven to the water station to provide illumination and ensure safety.

During the power outage, which continued for a long time, 53 Nissan LEAF vehicles supplied electricity at various locations in Chiba Prefecture. People who received electricity provided considerable positive feedback. This experience refreshed our awareness regarding the four advantages of supplying electricity from the Nissan LEAF system:

- Comfort provided by the quietness
- Safety attributed to the absence of an exhaust system
- Long-term energy attributed to the high-capacity batteries
- Capability of using multiple home appliances simultaneously because of the high discharge performance

Among these advantages, quietness and safety are particularly important during disasters. Facilities such as elderly care facilities are equipped with in-house electric power generators to prepare for natural disasters. Although preparedness is important, such power generators constantly emit loud noise, and there is a concern regarding carbon monoxide poisoning. Loud noises can make it difficult for people to sleep, which may cause stress. Furthermore, because gasoline, diesel, and other similar fuels are hazardous materials, handling these fuels may not be easy for employees of nursery or similar schools where small children are present. Further, EVs are advantageous because these problems do not occur.

In the following year, the EVs fully exerted their abilities in the damage recovery activity of a Japanese-style hotel when heavy rains hit Kumamoto in July 2020 (Figure 3). The usual response is to wash off the mud using hoses and brooms when a building experiences inundation above the floor level, and this method requires significant effort. However, high-pressure cleaning machines can be used to wash off mud and dirt when electricity is supplied from EVs, thereby significantly shortening the cleaning time.

Fig. 3 Electricity supplied from Nissan LEAF

More recently, eight Nissan ARIYA vehicles were lent to disaster-stricken cities such as Anamizu Town and Suzu City when an earthquake struck the Noto Peninsula in January 2024. Vehicles were used to supply electricity to shelters (Figure 4). Although this is a very difficult situation, many lessons need to be learned in terms of performing activities in areas that were far away from cities and where road conditions were not good.

Fig. 4 Electricity being supplied from Nissan ARIYA

In all case examples introduced above, a portable external power output device (V2L: Vehicle-to-Load) was used for directly supplying electricity to electrical devices. If a home or office is equipped with vehicle-to-home (V2H) equipment, that location can become a shelter by utilizing electricity from EVs. In city areas, where multifamily residentials and an increasing number of high-rise apartment buildings are provided for many people to live in, disaster prevention of the apartment buildings is a major issue. In these areas, EVs can be utilized as a countermeasure because they can supply electricity to elevators and other large equipment.

In 2023, in collaboration with Hitachi Building Systems Co., Ltd., a demonstration experiment was conducted in which electricity was supplied by Nissan's all-electric mini-vehicle, SAKURA, to operate the elevators and water supply units (Figure 5). Although SAKURA only has a relatively small battery capacity of 20 kWh, it can perform 15 h of continuous operation of the elevator installed in a six-story experimental building owned by Hitachi Building Systems. During the experiment, the elevator travelled 416 rounds. A demonstration experiment was conducted using a water supply pump. The pump supplied approximately 21.1 kL of water. Assuming that a person requires 2.5 L of water per day, the amount of water supplied can fulfill the requirements of approximately 8,500 people.

Fig. 5 Electricity being supplied from Nissan SAKURA

Although it is apparent that not all emergency electricity demands can be satisfied by EVs, securing emergency power supplies is an urgent issue in the context of preparedness against natural disasters because electricity is an important infrastructure for living in the present time. EVs can satisfy our requirements during both the "normal times" and "emergencies" as an automobile and as a high-capacity battery.

4. Energy Management

In March 2024, Nissan launched the "Nissan Energy Share" service, which utilized its unique energy management technology to control the charging and discharging of EV batteries.

"Nissan's Energy Share" is Nissan's unique technology, which is based on technologies and knowledge accumulated through various demonstration experiments. Featuring a charge–discharge controller connected to charging or charge–discharge units, the system predicts the energy usage of vehicles and obtains real-time information about the remaining charge of the vehicle as well as energy use in buildings, and autonomously determines the optimal timing for charging and discharging. This technology enables energy load shifting and peak shaving without compromising vehicle performance or comfort. Users can directly consume off-grid renewable energy produced onsite when connected to solar panels, thereby contributing to decarbonization. This service is a unique energy management system offered by Nissan, which has extensive knowledge of how EVs are used. This service is designed to enable optimal energy management in line with customer needs and circumstances and offers a one-stop service experience, from planning and system build-out to maintenance operations.

Nissan conducted several demonstration experiments on energy management before releasing its system. Please refer to the article "Activities regarding Vehicle Grid Integration" in this edition for details.

"Nissan Energy Share" is a solution that further unlocks the value of EVs, and the use of "Nissan Energy Share" is expected to grow steadily through the activities for realizing carbon neutrality and building future communities, utilizing the combination of "Nissan Energy Share," solar power, and EVs.

5. Circular Economy

The end of the service life of a gasoline and EV-mounted vehicle do not occur simultaneously. After the battery of an EV is used as a power source for ~10 years (i.e., until it reaches its service life), the battery retains the ability to store electricity (approximately 70% to 80% compared to a new battery) and can therefore be reused in various applications as an energy storage solution.

In September 2010, Nissan Motor Co., Ltd. and Sumitomo Corporation jointly established the 4R Energy Corporation to develop technologies and infrastructure to reuse, refabricate, resell, and recycle EV batteries (Figure 6).

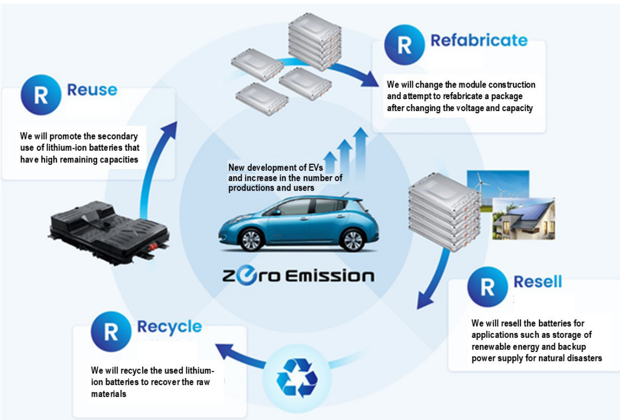

Fig. 6 About the 4R business

The service life of the recovered battery can be extended for another 10–15 years, which is far longer than that of lead batteries conventionally used as backup storage batteries. In grocery stores, where refrigerators and illumination need to be operated at all times, a backup power supply is necessary as a countermeasure against power network failures caused by power outages and natural disasters. This reused battery can sufficiently contribute to such cases.

The following is an introduction to fields in which recycled batteries are utilized.

The world's first reused-battery system was developed by the 4R Energy Corporation. Lithium-ion batteries used in 16 "Nissan LEAF" EVs were installed on Yumeshima artificial island in Osaka Prefecture. The batteries were used to store the electricity generated by solar panels. In Koshiki Islands in Kagoshima Prefecture, the reused batteries were utilized for storing electricity generated by the solar panels to develop the Koshiki Islands into "eco-islands" that have zero CO_2 emissions. Batteries facilitate a more stable power infrastructure on these remote islands, which often experience power outages.

A more familiar example is the East Japan Railway Company, which used recycled batteries as backup batteries for railroad crossings. Conventionally, lead batteries were used as backup batteries in the East Japan Railway Company to enable safety equipment for railroad crossings to continue operating during temporary power outages caused by accidents, natural disasters, and construction work. As part of the initiative to make railroad equipment more environment friendly, the company aimed to utilize recycled EV batteries and verify their performance. Their verification confirmed that the charging time of recycled batteries was s approximately 1/3 of that of conventional lead batteries. Further, it was anticipated that recycled batteries would have longer service lives than those of lead-based batteries. In addition, the stable operation of recycled batteries was confirmed in the environment in the vicinity of railroads. Therefore, the replacement of lead batteries with recycled EV batteries was started in January 2023.

The use of EV batteries as part of energy storage systems contributes to reducing CO_2 emissions and is a very effective method for realizing a stable supply of renewable energy. The value of EVs will increase further by providing additional value to batteries, which can lead to the widespread use of EVs.

6. Sustainable Tourism

The use of EVs in ordinary, familiar situations is being promoted for generating increased awareness about protecting the environment. Specifically, the use of EVs for transportation in tourism is promoted to consider the environment while enjoying the journey.

In 2021, Aso City (in Kumamoto Prefecture, where Mount Aso is located) and Nissan announced policies to incentivize the use of EVs. The aim was to boost the tourism industry by utilizing environment-friendly EVs. This policy targets tourists who use EVs for visiting tourist spots and roadside stations in Aso City. Discounts are offered at specified toll roads and tourist sites, and various hospitality services and privileges can be received if the tourist stays at specific hotels or Japanese-style hotels. This concept aims to help tourists enjoy the magnificent natural landscape of a region while using environment-friendly EVs.

After this activity started, it was expected to spread to Sasebo City of Nagasaki Prefecture in 2022; to 18 tourist driveways across the country (affiliated with the Japan Tourism Road Association) in 2023; and to the Minamiboso area of Chiba Prefecture, Sagamihara City of Kanagawa Prefecture, and the Lake Biwa area of Shiga Prefecture in 2024. This activity is gaining attention as a connection between EVs and boosts the tourism industry. In collaboration with the Nippon Travel Agency Co., Ltd. and 14 other companies, a new organization, the "GREEN JOURNEY Promotion Committee," that promotes eco-friendly travel, was established in August 2024, and proposed a new travel experience utilizing EVs.

In addition to using EVs for tourism, using EVs as power supplies in ordinary and familiar scenarios is gaining increasing attention. Examples include the use of EVs for environmental events, disaster prevention events, and various other types of outdoor events (e.g., town revitalization and illumination). Unlike power generators fueled by gasoline or diesel, EVs can realize quiet, clean, and environment-friendly events. Electricity discharged from EVs is compatible with music because of its stability. Therefore, in recent years, EVs have been increasingly used at music festivals and other similar events (Figure 7).

Fig. 7 Electricity supplied from Nissan LEAF at the BLUE EARTH MUSIC FEST 2023 IN MITO

The use of EVs can contribute to improving the eco-friendly image and reduce GHG emissions. In addition, visitors are expected to become more aware of the environment by offering opportunities to familiarize festival visitors with EVs.

7. Local Transportation

EVs are utilized as a solution to address issues in many provincial cities, including the downsizing of public transportation services. As an example of an activity to change these issues into promotion of sustainable development goals (SDGs), the details of "Comprehensive partnership agreement regarding solving social issues utilizing EVs," signed with Sango Town of Nara Prefecture in January 2020, were introduced below.

Sango Town was recognized by the Cabinet Office as the local government that makes excellent proposals regarding activities for achieving SDGs and selected as the "SDGs Future City" on July 1, 2019. Aiming at realizing "SANGO, a resilient and smart city for the people and the town," the members of the town proactively engage in activities for reducing environmental load, strengthening countermeasures against natural disasters, and solving social issues. Similar to other areas, buses are used as a means of public transport in Sango Town. However, the bus business did not go well. Therefore, a reservation-based share taxi system was introduced to replace buses to provide a mobility solution for elderly people and for others who do not have access to public transport, and the Nissan LEAF was selected as the taxi vehicle. In addition, V2H was installed in the town hall so that the Nissan LEAF could supply electricity to the town hall to enable it to function as a disaster control headquarters if power outages occur because of natural disasters (Figure 8). This single Nissan LEAF vehicle, which is utilized during normal times and natural disasters, contributes to decarbonization, provides solutions for transportation issues, and provides mitigation measures against natural disasters.

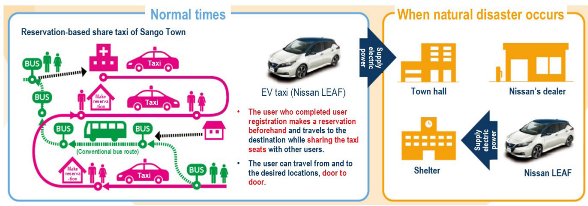

Fig. 8 Reservation-based share taxi of Sango Town

In Arao City, where the "Partnership agreement for achieving SDGs" utilizing EVs was signed in 2020, Nissan LEAF was introduced and operated as the on-demand share taxi (OMOYAI taxi). Anyone can use this taxi within any area of the city. The taxis can be used not only for shopping and going to the hospital but also for business purposes and tourism. In addition, the electricity generated within the area was charged to the taxi (Nissan LEAF), realizing the consumption of locally generated electricity.

In Nago City Hall, the official EV owned by the local government was rented for car sharing. The vehicle was used by city employees on weekdays and rented to tourists and local citizens on holidays so that the official EV vehicle was utilized effectively. This activity complemented public transportation services and contributed to the environment of the local community.

8. Educating the Next Generation

Environmental education is offered to children, who are expected to lead the next generation. It is hoped that communication with children about the activities of the automotive industry to tackle environmental issues and reduce the environmental load can help raise awareness about the environment among children and lead to their voluntary actions.

Nissan's original educational course "Nissan Waku-Waku Eco School" ("Waku-Eco") is a school visit program whose theme is environmental issues. The course offers a program that combines classroom learning (which introduces the issue of global warming, value of EVs for tackling the issue, and importance of utilizing renewable energy) and a model vehicle experiment (in the experiment, a simulation of a mobility society can be experienced). Employees of Nissan or the Nissan Group volunteered as teachers and supporters of the elementary school visit course. The teachers have in-house certification systems

The "Waku-Eco" course officially started in 2008. Initially, elementary schools in the vicinity were visited. Since 2019, with the help of our dealers, the course was provided across the country, and the number of attendees exceeded 140,000.

In addition, to cover the ocean plastic pollution problem, the eco caps collected in Ina City of Nagano Prefecture were upcycled to create a model car (Figure 9) to be used as the actual education material for the "Waku-Eco" course. Furthermore, the "Waku-Eco" course is sometimes incorporated in the contents of the Blue Switch agreement signed between Nissan and the local governments / companies. As described here, the activity of "Waku-Eco" continues to expand further. Environmental education is now offered beyond Japan, and in countries such as Great Britain, China, and Brazil. Education is provided by considering the needs of the destination.

Fig. 9 "Waku-Eco"educational material model car that was made using eco caps

9. Conclusion

There has been a gradual realization that EVs can be utilized as emergency power supplies when power outage occurs during natural disasters. However, there is little information about EVs and high hurdles when purchasing an EV. The EVs can contribute to society through mobilities that are more valuable than a simple means of transportation. Through activities that include reducing CO_2 emissions and employing electrification technologies into practical use, Nissan has pursued efforts to comply with environmental issues and create social value.

In the "Blue Switch" project, Nissan proactively promoted activities in collaboration with local governments and companies across the entire country to solve social issues by utilizing EVs.

As the leader of EVs, and with the hope of "making beautiful Japan even more beautiful with blue," Nissan will continue and strengthen its activities to realize a carbon neutral future through the widespread use of EVs.

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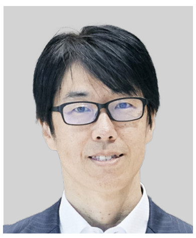
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4. Advances toward Carbon-neutral Factories Using Solid Oxide Fuel Cells

Satoshi Takaichi*　Shigeo Takahashi**　Toshiyuki Koide**

1. Introduction

Nissan is actively working to reduce CO_2 emissions throughout the entire vehicle life cycle, from raw material extraction and refining to vehicle manufacturing, transportation, use, and disposal. This can be accomplished by developing new technologies and introducing renewable energy sources throughout the value chain. A roadmap for achieving carbon-neutral Nissan facilities by 2050 has been announced, as shown in Figure 1[(1)].By 2030, we will reduce energy consumption in factories while promoting innovative production technologies and expanding the use of renewable energy.

Between 2030 and 2050, carbon neutrality will be achieved through the electrification of all facilities and the concurrent introduction of on-site power generation systems (Figure 2) using biofuels produced from sorghum, a plant in the Poaceae family, and solid oxide fuel cells (SOFCs). The CO_2 in the exhaust from these processes will be used to manufacture resin parts through methanation.

Indeed, carbon neutrality can be achieved more directly by developing in-house power generation to reduce dependence on the electrical power grid energy mix, which varies from country to country. Key considerations for doing so include realizing high-efficiency fuel cells and procuring carbon-neutral fuels, both of which have been studied at Nissan for many years. Nissan's efforts to apply these technologies to power its factories are discussed in this article.

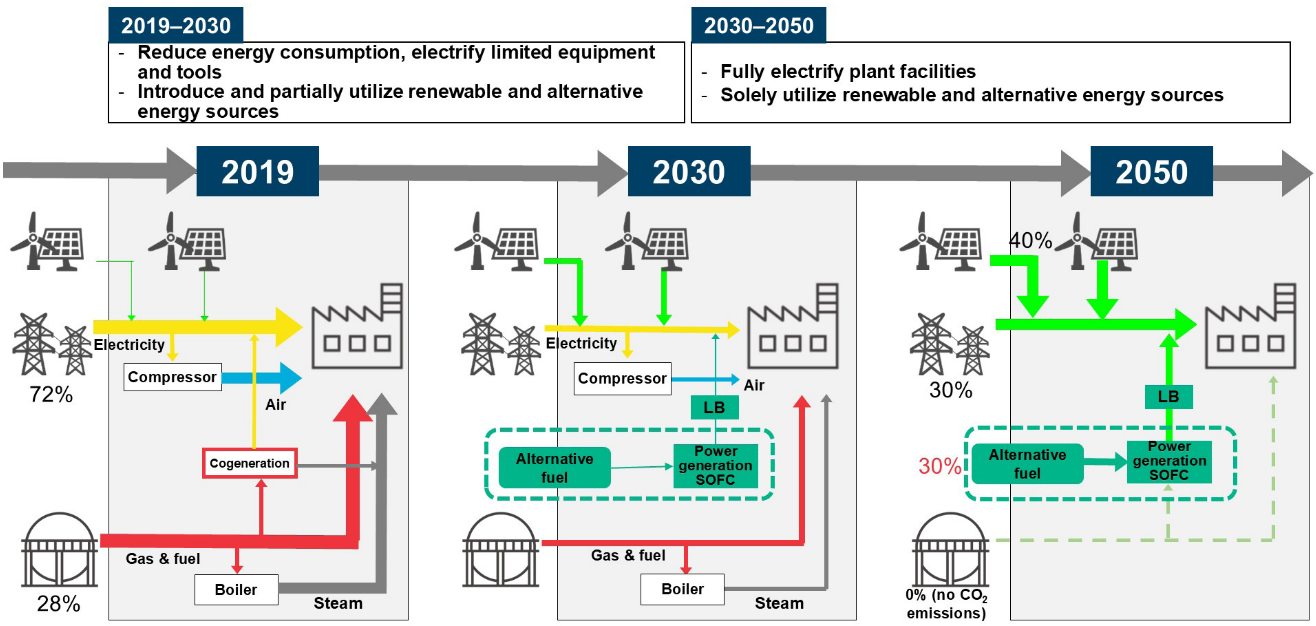

Figure 1 Overall efforts toward achieving carbon-neutral manufacturing plants

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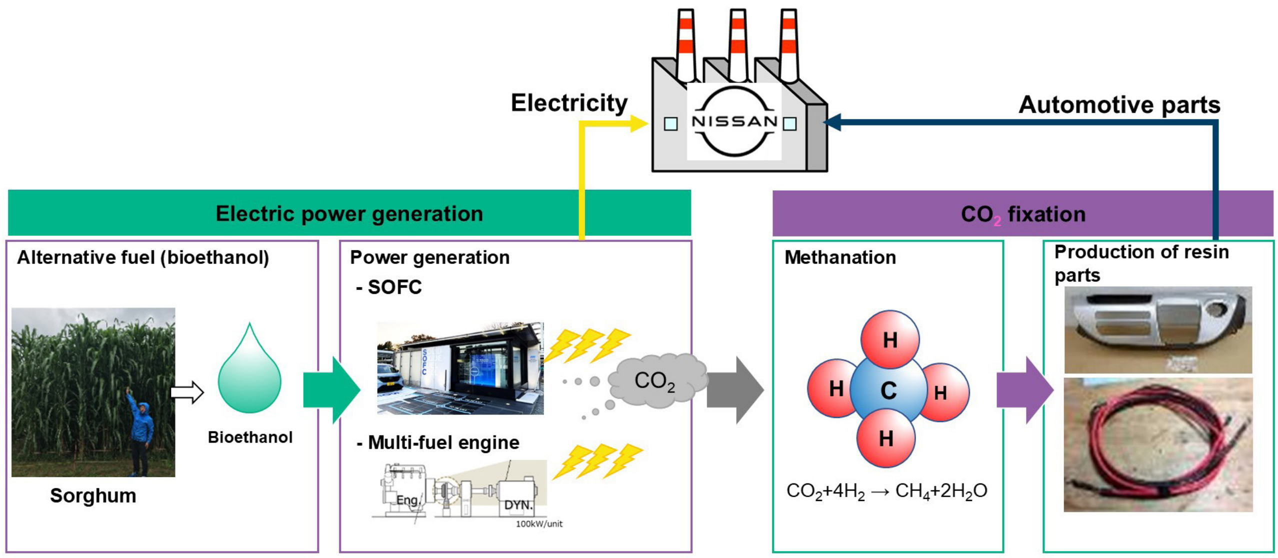

Figure 2 On-site alternative energy power generation facilities

2. Fuel cells

2.1 Types of fuel cells

Two types of fuel cells have attracted significant attention as power sources for automobiles: polymer electrolyte fuel cells (PEFCs) and SOFCs (Figure 3). Fueled by pure hydrogen, PEFCs generally operate at relatively low temperatures (below 100 ℃). Their advantages include responsiveness to the output demand and excellent power density, making them well-suited for use as power sources in electric vehicles, which require a high initial power output to provide motive force. However, the low operating temperature of a PEFC limits the catalytic activity within, requiring the use of expensive precious metals such as Pt to compensate.

In contrast, SOFCs use hydrogen produced by reforming various fuels, such as hydrocarbon gases (methane and propane) or liquids (methanol and ethanol). They can operate at temperatures over 600 ℃, facilitating excellent catalytic activity and highly efficient operation. However, SOFCs require a long startup time because they can only operate at high temperatures; rapid startup risks damaging the ceramic materials used in the cell through thermal shock. Furthermore, the high operating temperature also induces a high electrical resistance, making SOFCs unsuitable for high-power output. Finally, the power density of an SOFC is lower than that of a PEFC. These issues have limited the application of SOFCs to stationary power sources for households and industries requiring steady power, rather than as automotive power sources that must provide rapid startup in a small size.

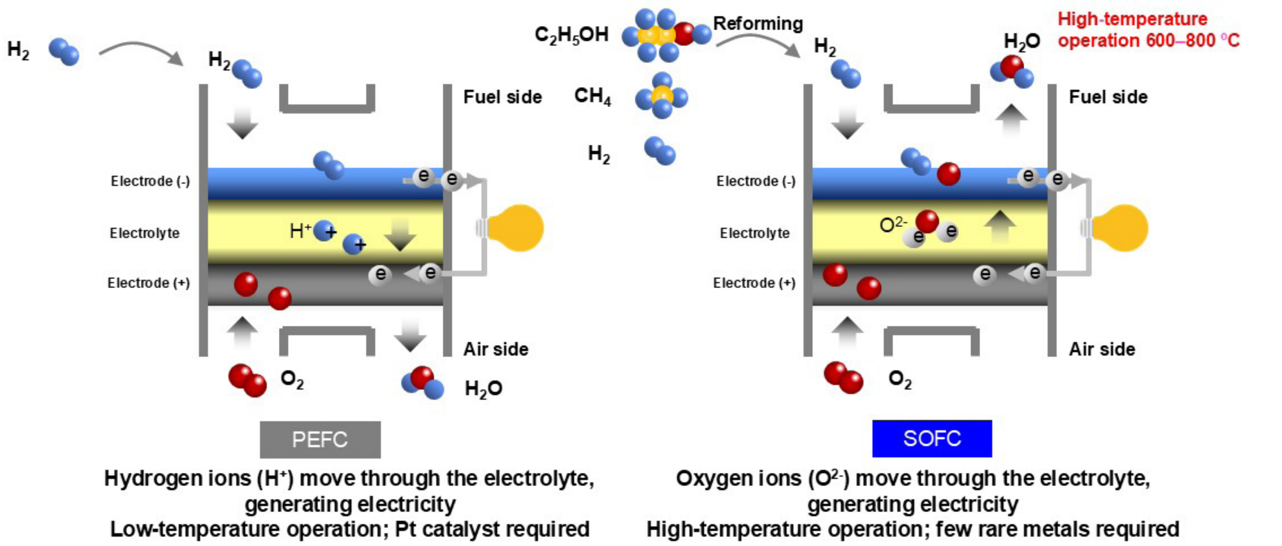

Figure 3 Schematics of PEFC and SOFC operation

2.2 Development of SOFC vehicles

Given the excellent efficiency associated with SOFCs, they have been considered a potential power source for commercial vehicles that require relatively infrequent startups. A concept fuel cell vehicle equipped with the "e-Bio Fuel Cell," a SOFC system fueled by bioethanol, was introduced by Nissan in 2016 accordingly (Figure 4).

Specifications of research prototype vehicle

Features	Specs.
Base vehicle	e-NV200
Battery Capacity	24kWh
Powertrain	Electricity
	100% Ethanol
Fuel tank capacity	30L
SOFC power	5kW
Driving range	Over 600km

Figure 4 e-Bio Fuel Cell concept vehicle

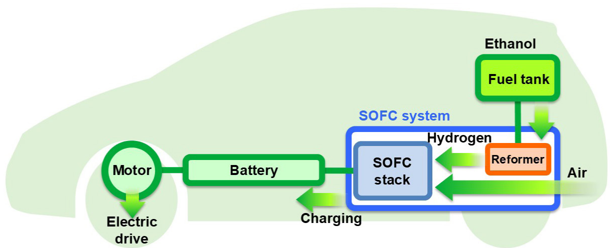

Figure 5 e-Bio Fuel Cell system

The configuration of the e-Bio Fuel Cell system is shown in Figure 5. To compensate for the low power density of the SOFC, the SOFC is used as an EV range extender; the power generated by the SOFC is charged in a battery and the charged energy is used to drive the motor. Notably, SOFCs can utilize existing distribution networks because the required ethanol is a common liquid fuel. This provides SOFC-based vehicles with an infrastructural advantage over PEFC vehicles, which require pure hydrogen fuel. In addition, the combination of an SOFC, which provides high power-generation efficiency, with a liquid fuel, which provides a high energy density, facilitates a long driving range (over 600 km) with a filling time comparable to that of a gasoline-powered vehicle. Consequently, vehicles using SOFCs can be expected to provide a similar driving experience. r.

Research is underway to address the remaining issues hindering the application of SOFCs. For example, metal-supported SOFCs are being developed to accelerate startup time. Figure 6 compares the results of thermal shock tests performed on metal-supported and conventional ceramic electrode-supported SOFCs. When a large temperature difference of 250 °C was applied to the cell surface to simulate the temperature distribution during rapid vehicle startup, the metal-supported SOFC exhibited no damage, whereas the conventional SOFC exhibited extensive damage. In addition, the high mechanical strength of the metal-supported layer permits the use of a thinner metal support layer, further reducing the thermal capacity of the cell. Clearly, metal-supported cells represent a critical technology for improving the power density and reducing the startup time of SOFCs in automotive applications.

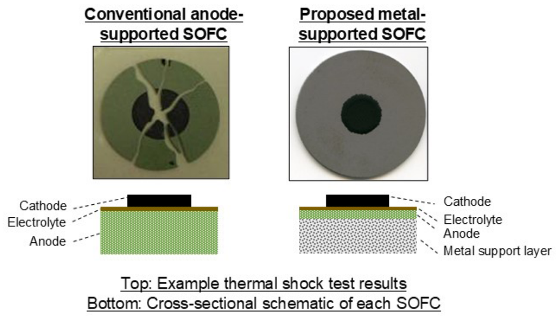

Figure 6 Thermal shock test results for conventional ceramic electrode-supported and novel metal -supported SOFCs

2.3 Stationary fuel cell systems

Nissan's work on vehicle-mounted SOFC technology has been applied to develop a stationary power generation system presently in trial operation at the Tochigi plant (Figure 7). As shown in Figure 8, this system draws ethanol from the fuel tank to supply the reformer, where the ethanol is reformed to hydrogen subsequently supplied to the SOFC stack. The power generated by the SOFC can be sent to the grid, stored in an energy storage system, or used to charge electric vehicles. The trial operation of the SOFC system at the Tochigi plant represents the first step toward the full-scale application of SOFC systems at all Nissan plants. Similar SOFC systems are planned to be installed globally once the quantity of electricity generated by the trial system at the Tochigi plant has been increased and sufficient experience with this configuration has been gained.

Figure 7 SOFC system installed at Nissan's Tochigi plant

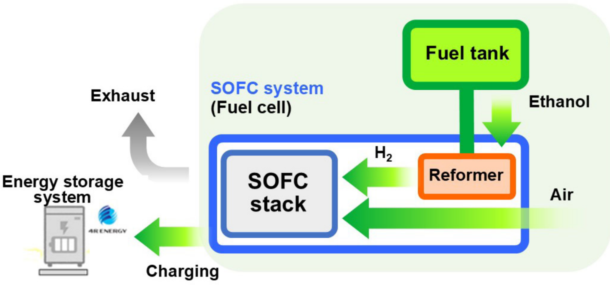

Figure 8 Overview of the SOFC power generation system

3. Bioethanol procurement

3.1 Bioethanol

The procurement of carbon-neutral bioethanol is a critical aspect of carbon-neutral energy generation. Therefore, a partnership between Nissan and Binex Co. is developing the use of sorghum (Figure 9) as a feedstock for the production of bioethanol. Approximately 40,000 varieties of sorghum exist, but the sorghum employed in this process has four critical characteristics:

(1) It is an annual plant that grows quickly and can be harvested in approximately three months, allowing for multiple harvests each year in suitable growing regions.
(2) It is well-adapted to cold and arid regions, enabling its cultivation in a wide range of environments and soils.
(3) Its stems can be used to produce second-generation bioethanol that leaves the fruit for use as food.
(4) The stem waste (bagasse) remaining after solution extraction can be utilized for biomass power generation.

These characteristics can help realize a stable supply of sorghum feedstock that is relatively unaffected by climate and weather conditions. In the future, bioethanol produced from sorghum is planned to be adopted at the Tochigi plant and other production plants worldwide.

Figure 9 Sorghum under cultivation

3.2 Demonstration of sorghum cultivation

As shown in Figure 10, the sorghum used in Nissan's SOFCs will be grown in Australia, which is also where the extracted sugar solution will be processed into bioethanol and the bagasse will be pelletized. A small-scale test demonstration of sorghum cultivation is already underway in Australia to identify potential issues in three processes:

(1) the pressing of cultivated sorghum to extract a sugar solution,
(2) the production of bioethanol by fermenting and distilling the sugar solution,
(3) the importation of bioethanol into Japan by sea freight to supply power generation facilities, such as SOFCs.

Trials of these processes will be conducted along with feasibility studies on the use of bagasse, a byproduct of the process, as a fuel for biomass power generation to facilitate future mass production.

Notably, sorghum-based bioethanol is not only beneficial because of its environmental friendliness but also because it can reduce energy costs while providing an energy source that is highly robust against resource risks.

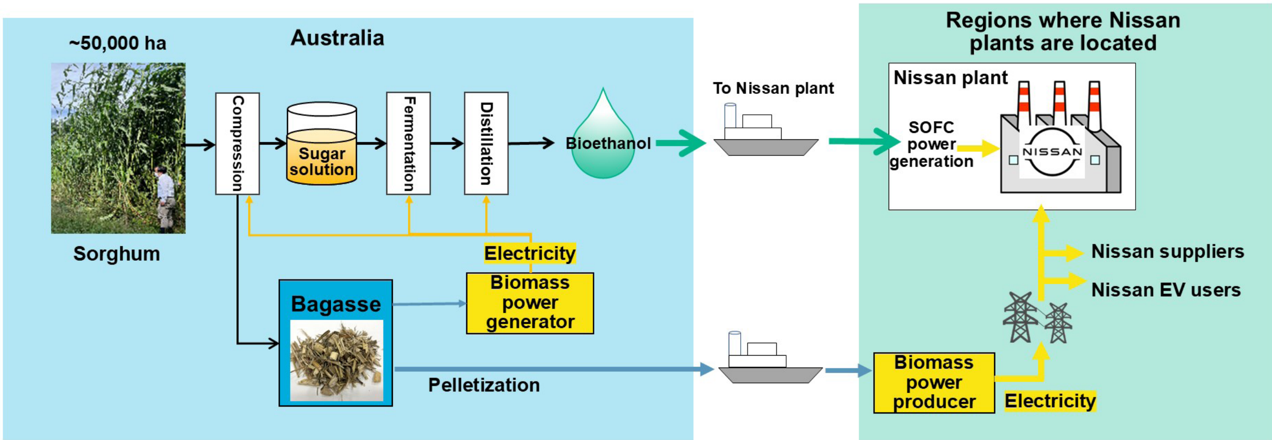

Figure 10 Process of sorghum ethanol production from harvest to factory power supply

4. Conclusion

This report describes Nissan's efforts toward realizing carbon-neutral factories. Critically, the energy mix of power grid electricity varies between countries and regions, hindering efforts to achieve carbon neutrality when relying on the grid as an energy source. The laws and regulations regarding fuel procurement also differ among countries and regions, as do the available fuels. Therefore, a device that can efficiently convert a wide variety of fuels into electricity is required; SOFCs show significant promise in such applications (Figure 11).

Efforts to develop a highly efficient SOFC have been underway for many years at Nissan. Although this technology was originally intended to be applied in vehicles, stationary applications of SOFCs are subject to fewer size and startup time constraints. Therefore, SOFCs will first be employed in stationary applications, such as factories, and then eventually expanded to use in automotive applications as the technology develops. However, the number of partners and production resources must be increased to reduce costs and extend SOFC use beyond stationary and automotive applications to various mobile applications, leading to the widespread use of SOFCs.

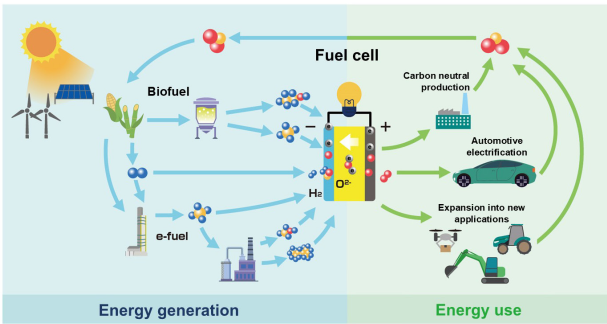

Figure 11 Potential roles of SOFCs

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Authors

Satoshi Takaichi

Shigeo Takahashi

Toshiyuki Koide

5. EV36Zero and Carbon Neutrality Initiatives at Sunderland Plant, United Kingdom※

Ryota Ikumi*

1. Introduction

The automotive industry is undergoing major changes in business structure as it works to reduce its CO_2 emissions and eliminate fossil fuel dependence. As a global automaker, Nissan is working to reduce CO_2 emissions without compromising corporate activities by developing new technologies and using renewable energy sources while considering CO_2 emissions throughout the entire value chain (including suppliers) from procurement and transportation of raw materials to vehicle operation. The primary source of CO_2 emissions during vehicle production is fossil fuel energy consumption. Various energy-saving activities are being developed to help Nissan consume the least energy and emit the least CO_2 of any automaker. Indeed, Nissan has committed to achieving carbon neutrality in its corporate activities throughout the lifecycle of its products by 2050 (Figure 1). The electrification of vehicles and innovation in manufacturing technologies are expected to play critical roles in these efforts to become carbon neutral. Efforts to reduce CO_2 emissions from vehicle and powertrain manufacturing plants are also being promoted globally.

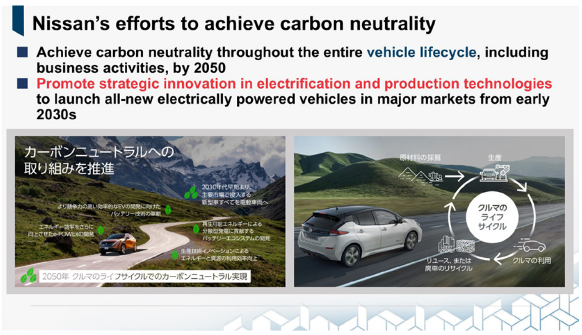

Figure 1 Carbon neutrality initiatives at Nissan

2. Initiatives at Nissan Sunderland plant: EV36Zero

2.1 Nissan Sunderland plant

The Sunderland plant is located in northeastern England and is Nissan's largest production base in Europe, manufacturing more than 11 million vehicles since it began operations in September 1986. The Sunderland plant employs approximately 6,000 people and has an annual production capacity of 440,000 vehicles. As of 2024, this plant produces three models (the QASHQAI, JUKE, and LEAF) for sale in the United Kingdom, Europe, and the rest of the world. Carbon neutrality initiatives at the Sunderland plant began with the installation of ten wind turbines generating 6.6 MW of electricity in 2005 and continued with the installation of a photovoltaic system generating 4.75 MW of electricity in 2016. Continuous efforts have been undertaken since then to expand the renewable electricity capacity of the Sunderland plant and reduce the CO_2 emitted by its production operations.

2.2 Overview of EV36Zero

The EV36Zero production strategy was announced at the Sunderland plant in July 2021 to accelerate efforts toward achieving carbon neutrality and establish a new 360° solution for realizing a zero-emission society. Nissan's mid-term management plan, The Arc, is committed to expanding this strategy to other plants in Japan and North America (Figure 2).

Figure 2 Expansion of EV36Zero

※ This text is based on the data at the time of writing (October 2024).

*Strategy and Planning Department

This innovative project is structured around three initiatives (Figure 3): (1) production of next-generation electric vehicles (EVs) beginning at the Sunderland plant in 2025; (2) construction of a new plant for the Envision Automotive Energy Supply Corporation, which provides the world's most advanced battery technology, next to the Sunderland plant; and (3) development of the International Automotive Manufacturing Park (IAMP) for suppliers near the Sunderland plant under the leadership of the Sunderland City Government. A microgrid will be deployed at the IAMP to increase the generation of renewable energy and manage the sharing of this energy among Nissan and its partner companies. Approximately £1 billion will be invested in these three EV36Zero initiatives, which were made public in July 2021. EV36Zero consists of EV, renewable energy, and battery production initiatives, and is a production strategy that lays out a blueprint for the future of the automotive industry.

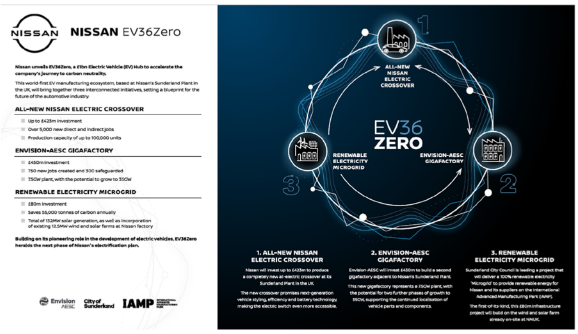

Figure 3 Overview of EV36Zero

Additional plans were announced in December 2021 to significantly expand renewable energy generation facilities at the Sunderland plant by installing a new 20 MW solar photovoltaic facility. Completion of this facility doubled the renewable energy generation capacity of the plant, which now provides 20% of the electricity used at the plant and is sufficient to power the production of all Nissan LEAF vehicles sold in Europe.

An update to EV36Zero was presented in November 2023 announcing that Nissan would produce two new EV models in the future with an additional total investment of approximately £2 billion (Figure 4).

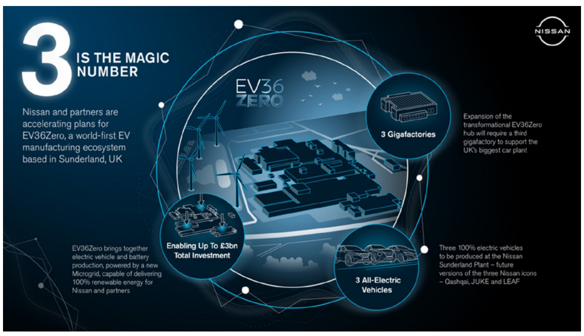

Figure 4 EV36Zero update

3. Carbon neutrality initiatives at the Sunderland plant

Nissan's approach to achieving its carbon-neutrality goals for production focuses on five aspects to reduce CO_2 emissions to 50% of their 2018 level by 2030 (Figure 5):

- reduction of energy consumption
- electrification of equipment and tools
- introduction of renewable energy
- power generation using alternative energy sources
- utilization of carbon credits.

In pursuit of this policy, the Sunderland plant has been working to realize the lowest CO_2 emissions among all Nissan plants by utilizing and expanding wind and solar power generation, as mentioned previously, and implementing efficiency measures, including systems to continuously monitor power consumption at plant facilities and improve power on/off management. Future initiatives include plans to introduce large EV battery-based power-storage facilities and adopt alternative energy sources, such as bio-methane gas. This will accelerate the reduction in plant-derived CO_2 emissions to exceed the rate required to meet the 2030 target.

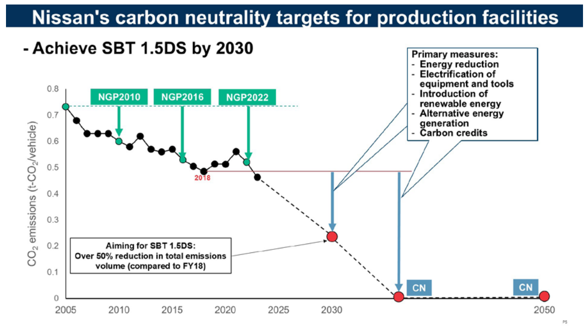

Figure 5 Overview of EV36Zero plan stages

4. Future development

The EV36Zero production strategy aims to continuously improve the competitiveness of production sites by producing future vehicle models while achieving carbon neutrality through collaboration between Nissan, its partners, and local governments. Ongoing efforts to develop EV36Zero at the Sunderland plant are underway in partnership with the Sunderland City Government to address four aspects (Figure 6):

(1) providing sustainable housing through renewable energy and vehicle-to-everything technology (sustainable living);

(2) fostering recycling-oriented businesses that aim to reuse limited resources (circular economy);

(3) expanding local employment, providing educational opportunities, and conducting joint research with universities and technical colleges (skills for the future);

(4) implementing carbon-neutral and sustainable manufacturing methods such as digital transformation and automated logistics (sustainable manufacturing).

By progressing in these directions, Nissan can secure its competitiveness in the future manufacturing industry while contributing to carbon neutrality and working as a member of the local community.

Notably, Europe is home to many well-established original equipment manufacturers, strict environmental regulations, and strong market sensitivity to environmental issues. As EV36Zero is being carried out in this environment through collaboration with local governments, business partners, and educational institutions, it should be considered a model for efforts in Japan and other regions in the near future. Indeed, EV36Zero is being expanded to Nissan production sites around the world under The Arc mid-term plan.

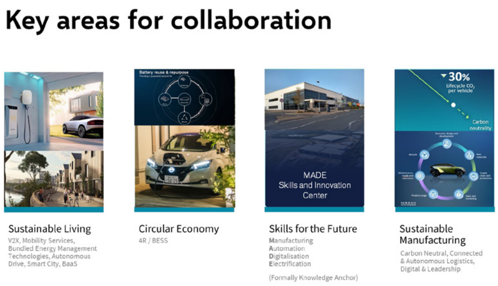

Figure 6 Further initiatives

Authors

Ryota Ikumi

6. Activities related to Vehicle Grid Integration

Keigo Ikezoe*

1. Introduction

In January 2021, Nissan announced its new goal to achieve carbon neutrality by 2050; this goal includes the entire vehicle lifecycle and Nissan's business activities. As a vehicle manufacturer, achieving decarbonization entails reducing CO_2 emissions during manufacturing and taking responsibility for minimizing CO_2 emissions after our products are delivered to our customers (when the vehicles are used, fuel is produced, and electric power is produced), which as shown in Figure 1, accounts for a large proportion of the total emissions. Therefore, achieving the simultaneous mass adoption of renewable energies (REs) is necessary when promoting the widespread use of EVs. When aiming to achieve decarbonization as a vehicle manufacturer, it is necessary for the EVs to run on electricity generated by REs.

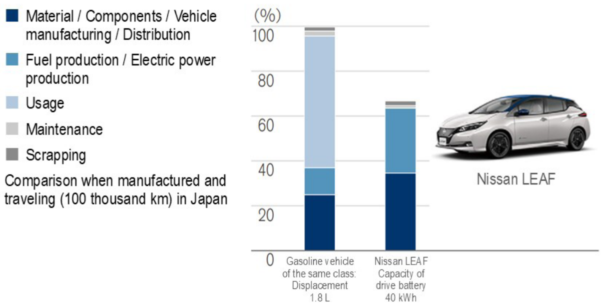

Fig. 1 CO_2 emissions encompassing the entire vehicle life cycle compared between EVs and gasoline vehicles[1]

In general, it is not possible to control the power generation amount of REs such as solar and wind power generation. Therefore, enhancing the capacity for supply-demand balancing in electric power systems is necessary to achieve mass adoption of REs; this can help the electric power systems to operate with better economic efficiency when the adoption of REs becomes widespread. Meanwhile, from the viewpoint of EV users, this is acceptable as long as the EV is charged before it is used again. Therefore, the period within which the EV is charged (i.e., the period in which the electric power of the system is used) can be changed in a flexible manner. In other words, EVs have the unique characteristic of "flexibility in the timing of electric power demand (timing of using electric power)," which is not provided for other devices that consume electric power.

The concept of leveling the power supply and demand using EVs by utilizing the characteristics described above is referred to as vehicle grid integration (VGI) and has been promoted proactively by Nissan.

Figure 2 shows the vehicle-to-building (V2B) demonstration experiment conducted in Namie Town, Fukushima Prefecture. The Nissan LEAF vehicles used in the experiment were introduced as official vehicles in the town. In this demonstration experiment, the electric power generated by solar power generators installed on the roof of an adjacent roadside station was used proactively to charge the EVs. Electric power management was implemented to discharge electric power from the EVs for suppressing the peak when the electric power demand in the building approached its peak[2].

Fig. 2 V2B demonstration experiment in Namie Town, Fukushima Prefecture

Nissan performed similar demonstrations worldwide. Based on this experience, Nissan launched the "Nissan Energy Share" service on March 1, 2024, which utilizes EVs and offers comprehensive energy management

*EV System Laboratory

solutions ranging from planning to operations[3]. The Nissan Energy Share service is already operational at Gunma Nissan Motor Co., Ltd. (Figure 3)[4] and Hiroshima University (Figure 4)[5]. Our customers, who had the vision and comprehensive strategies for realizing carbon neutrality, introduced this service as a component of their businesses because they shared the same values.

Fig. 3 Example of the introduction of Nissan Energy Share in the Quality Assurance Center of Gunma Nissan Motor

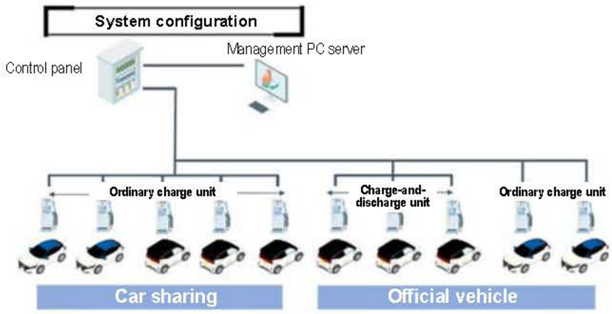

Fig. 4 (a) Example of the introduction of Nissan Energy Share in Hiroshima University

Fig. 4 (b) Example of the introduction of Nissan Energy Share in Hiroshima University

Nissan proactively promoted VGI via co-creation with people outside the company. This activity is based on our belief that EVs provide a significant effect on electric power systems, which are the systems used in our society. Therefore, the level of impact that EVs provide is presented quantitatively using a numerical analysis method in Sections 2 and 3. Further, Section 4 provides case examples of co-creation activities with local communities and other industries to expand VGI activities.

2. Effect of the widespread use of EVs on electric power systems

The amount of energy consumed in the form of gasoline can be replaced by electricity if the use of EVs becomes widespread in the future. Consequently, there is a concern that an enormous load will be applied to electric power systems.

Meanwhile, 95% of all the vehicles are parked. Therefore, there is a very high flexibility in the time of day when an EV can be charged. There will be no need to enhance the capacity of the electric power systems when management is implemented for charging EVs when the total demand in the electric power system is relatively low or when excessive electricity is generated by REs; the economic efficiency of the REs will increase as well.

This section presents the effect of EV mass adoption on electric power systems based on the results of a quantitative evaluation performed using a simulator. The simulator was developed in-house and capable of performing case studies using different parameters.

2.1 Method

The Nissan Research Center developed a tool to calculate the hourly electricity demand for charging EVs. The calculations are performed based on the input of various constraint conditions and statistical data, such as the specifications of future EVs; future status of the establishment of charging infrastructures; and vehicle usage patterns, which differ for each region[6]. In the course of the development, basic data representing the statistical analysis of the usage data of approximately 11,000 EVs were generated. The Monte Carlo method was adopted for the calculations. In this method, the statuses of the agents were shifted based on multiple types of probability distributions to enable the execution of continuous simulations for multiple days in a short amount of time. Therefore, it is possible to perform case studies with various parameters, which enables computational experiments to analyze the effects and side effects of implementing various policies regarding EV charging.

2.2 Statistical analysis of EV usage data

Figure 5 shows examples of EV usage data required for the simulation. These data were created by statistically processing the data acquired through telematics from actual EVs (telematics data). Although EVs are typically charged at the home or workplace of a user, the charging cable may not always be plugged in if the EV is parked.

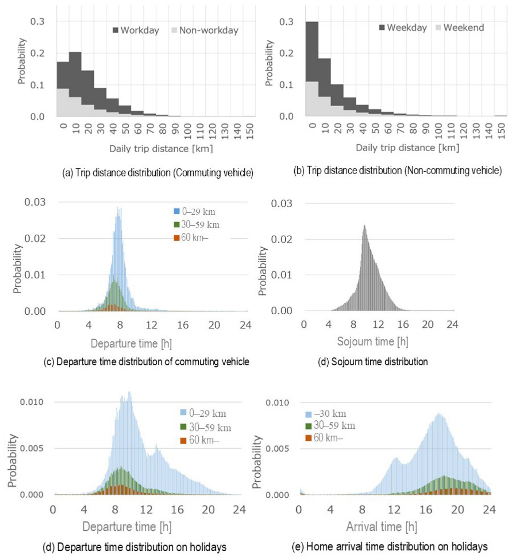

Fig. 5 Examples of the probability distributions of behavior of EVs created using telematics data from LEAF vehicles

For example, the user may not take the time to plug in the charging cable if the battery level (SOC) is sufficiently high to cover the driving range. Therefore, a plug-in behavioral characteristic model was created using telematic data to incorporate this behavioral characteristic into the simulator. Figure 6 shows the relationship between the plug-in probability and SOC at the time of arrival at home or the workplace. This graph indicates the behavioral characteristics, where the plug-in probability becomes low if the SOC is high when the user arrives at home (workplace), whereas many users plug in the charging cable if the SOC is low upon arrival. This tendency differs between homes and workplaces. This probability distribution shows the behavioral characteristics of users whose telematics data were acquired between 2015 and 2016. This trend is anticipated to differ significantly depending on the battery capacity, occupancy status of the charging facilities at the workplace or home, and on whether the use of automatic charging will become widespread in future. The simulator developed in this study can accept the probability distribution representing plug-in behavior characteristics as input data. Thus, parametric studies can be performed by assuming various future scenarios.

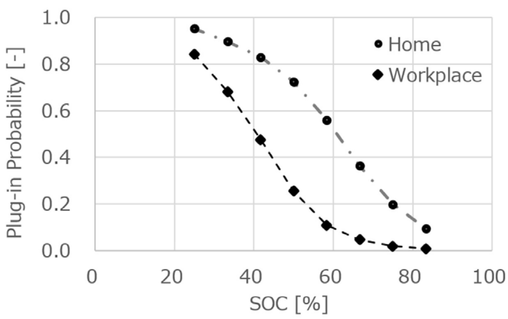

Fig. 6 Plug-in probability (When charging at home or at the workplace)

2.3 Calculation of electricity demand caused by charging the EVs

Figure 7 shows the flow for calculating the curve of the hourly electricity demand caused by charging the EVs using probability distributions based on how EVs are used and the charging behavior model. In the simulator, users were classified into those using EVs to commute (commuters) and those using EVs other than commuting (non-commuters). Subsequently, the agents were generated based on a specified ratio. The behavior in each step was selected using a random number in accordance with the probability distributions. The electric power charged by all agents was summed over time to calculate Pt, which is the electricity demand caused by charging the EVs (Equation (1)).

$$P_t = \sum_{i=1}^{n_1} P(com)_{t,i} + \sum_{j=1}^{n_2} P(non\_com)_{t,j} \qquad (1)$$

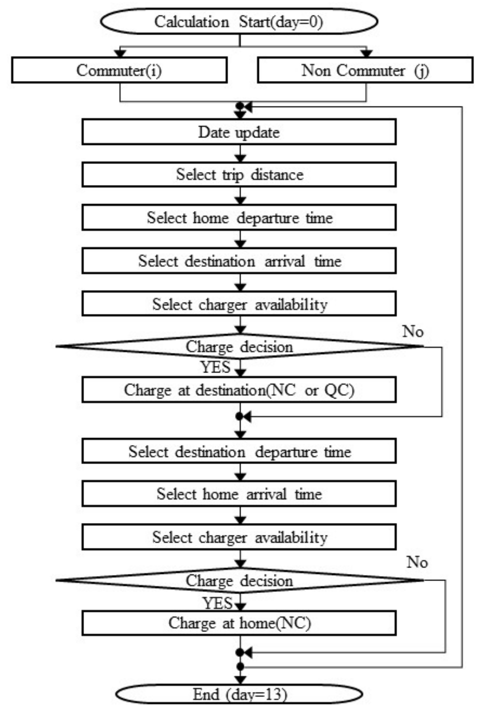

Fig. 7 Flow of Monte Carlo simulation for calculating the charging demand curve

2.4 Calculation results

2.4.1 Basic conditions and their calculation results

Figure 8 shows the electricity demand attributed to charging the EVs (using parameters listed in Table 1 as basic conditions) with respect to the actual electricity demand within the service area of Tokyo Electric Power. The daily load curve for the case “maximum electricity demand during summertime” was used for the electricity demand besides the demand for EVs[7]. It was assumed that the EV adoption ratio around 2040 would be 35% and the number of vehicles within the service area of

Tokyo Electric Power would be 6.5 million vehicles. Further, it was anticipated that EVs would usually be charged in residential areas from the evening to nighttime. Therefore, in this article, the daily load curves of the household and industrial sectors were shown separately for analyzing the impact provided to each of them. As shown in Figure 8, the time of returning home and the evening peak electricity demand of the household sector overlapped. In this case, the electricity demand attributed to charging EVs will be added to the peak electricity demand in the household sector; this is a concern because it can adversely affect the electric power systems in residential areas. This result was designated as the "base case where no management is implemented for EV charging (consequential charging)." Considering the base case as reference, parameter studies were conducted by varying the parameters, and the results were analyzed further.

Table 1 Initial prerequisites for simulating the electricity demand caused by EVs

	Commuter	Non-commuter
EV penatration	35% of private passenger vehicle	
Commuter/Non-commuter	50%	50%
Home charger ratio	100%	100%
Destination charing	(workplace) 0%	0%
Ratio to go out	90%	70%
Battery capacity	24kWh	24kWh
Normal charging	3kW	3kW

2.4.2 Results of taking account of the nighttime electricity rate

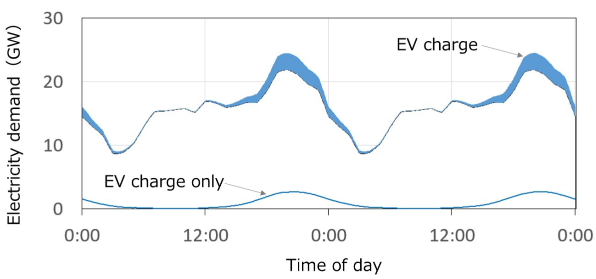

Fig. 8 Results of simulating the charging demand (case where no management is implemented for EV charging)

In some regions, the nighttime electricity rate is set to a lower value so that EV charging does not overlap with the evening peak electricity demand. However, when the simulator analysis was conducted considering these conditions, the results showed a new peak at the shifted charging hours (Figure 9). The results indicated that there was a need to design a management method such that the shifting amount or shifting hours would be dispersed within the same electricity distribution network if EV charging needed to be shifted after the use of EVs becomes widespread.

2.4.3 Effect of the adoption rate of home and

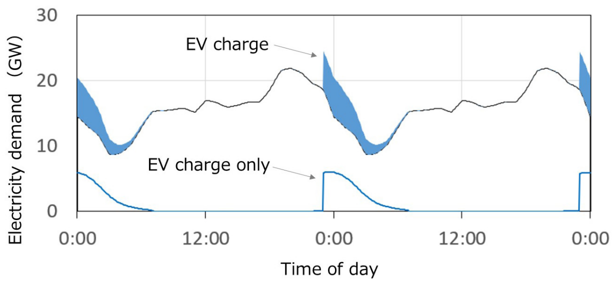

Fig. 9 Results of simulating the charging demand (case where the nighttime electricity rate is applied from 11:00 p.m.)

workplace charging

A parameter study was conducted for EV users who lived in multifamily residences or similar places and did not own EV chargers at home, if commuters of such users charged their EVs at the workplace. The results of this study are presented in Figures 10 (a) and (b). In the obtained results, the peak attributed to the nighttime electricity rate decreased by more than half with a decrease in the frequency of charging at home. This decreased demand was added to the electricity demand of the industrial sector.

Charging in the workplace was found to be advantageous, as indicated in Figure 10 (b). The electricity generated by the REs was used effectively because the charging hours aligned with the hours of excessive electricity generation by solar power generators. Therefore, promoting the introduction of EV chargers in workplaces is considered an effective policy from multiple perspectives, such as the reduction of CO_2 emissions from the electricity sector, reduction of investments in rapid charging facilities, and decrease in peak electricity demand of the household sector. The electricity supply curve for solar power generation shown in Figure 10 (b) assumes that 27 GW of solar power generators are introduced by 2030 based on the disclosed actual power generation value within the service area of the Tokyo Electric Power in 2017.

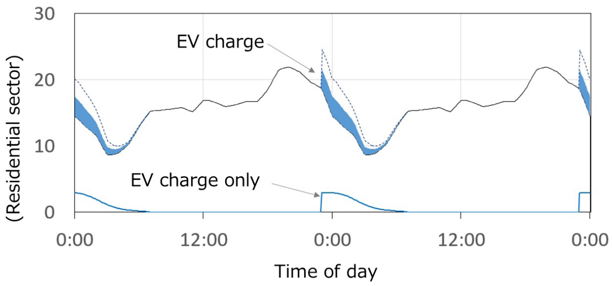

Fig. 10 (a) Results of simulating the charging demand (case where charging at the workplace has become common)

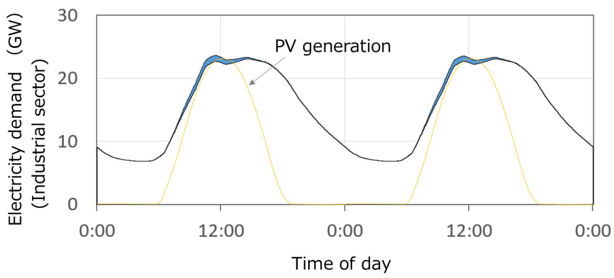

Fig. 10 (b) Results of simulating the charging demand (case where charging at the workplace has become common)

2.5 Using the simulator to understand future issues in advance

This section introduces a simulator that can quantitatively visualize the impact of changing various parameters on electric power systems. The simulator incorporated the EV charging behavior model created using the actual usage data of approximately 11,000 EVs. In future, if there are changes in the EV specifications (e.g., capacity of the mounted battery), status of the established charging infrastructures or other social scenarios, such conditions can be set in the simulator as input parameters. The effects of charging EVs on electric power systems under these conditions can be understood in advance. Thus, countermeasures can be implemented before problems occur.

3. Effect of introducing VGI on the reduction of CO_2 emissions

The impact of charging EVs on electric power systems and the need to implement impact management were described in the previous section. From a different perspective, the batteries can help avoid excessive power generation by REs and reduce fuel consumption by thermal power plants if the batteries of the widely used EVs are utilized for demand balancing electric power systems. This section presents the results of the quantitative calculation of the CO_2 emission reduction effect.

3.1 Method

The unit commitment model developed by Udagawa et al. [8][9] was used to simulate the electric power systems in this study, and the EV model was applied to calculate the CO_2 emission reduction effect of the VGI[10]. Figure 11 shows a conceptual illustration of the electric power system used in the simulation. The objective function of this model is minimizing the operational costs of thermal power generators (including fuel costs, startup costs, and carbon taxes), which is formulated as a mixed-integer programming problem. In addition, balancing the power supply and demand and securing the necessary load frequency control (LFC) reserve are set as constraint conditions. The calculations of this model were performed in two steps: the day-ahead plan using the solar power generation output forecast values and the same-day operations using actual measured values. Three scenarios were considered to quantify the CO_2 emission reduction effect of the VGI: (i) Consequential charging, (ii) management implemented for charging, and (iii) management implemented for charging and discharging.

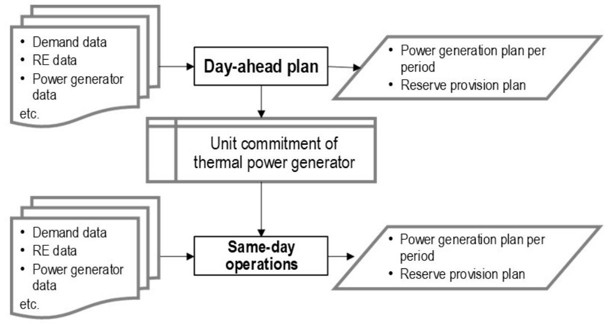

Fig. 11 Conceptual illustration of the simulation of the electric power system

3.2 Prerequisites for calculating the CO_2 emission reduction effect

3.2.1 Conditions of the electricity supply–demand system and conditions of the EVs

The service area within the Kyushu Electric Power in 2030 was selected as the analysis target. According to the predictions provided by the Agency for Natural Resources and Energy, the electricity demand in 2030 is expected to be 864 billion kWh[11]. The capacities of the RE facilities were set to 21.8 GW[12] and 4.7 GW[13] for solar and wind power generation, respectively. The CO_2 emission factors were set as 795, 376, and 695[14] g-CO_2/kWh for coal-fired, LNG-fired, and oil-fired power generation, respectively. The carbon tax was set at 20,000 yen/ton-CO_2. As a prerequisite for calculating EV adoption, the number of vehicles in Japan was set to 68 million. The number of EVs in the Kyushu area was set to 320,000 vehicles considering the ratio of passenger vehicles in the Kyushu area (11%) and the EV adoption ratio in 2030 (4.3%)[15]. In the calculations in this study, it was assumed that all EVs parked at home and the workplace were plugged into the charge and discharge units. This assumption was made to evaluate the maximum CO_2 emission reduction effect, which accounted for reducing fuel consumption in thermal power plants realized by the VGI. LEAF e+ (battery capacity of 62 kWh) was selected as the model for the EVs. The initial SOC, charging/

discharging power, charging/discharging efficiency, and electrical energy consumption were set as 50%, 6 kW, 90%, and 7 km per 1 kWh, respectively.

3.2.2 EV cluster model

An EV cluster model was created to apply EV characteristics as input parameters to the abovementioned electric power system model. In this model, 10,000 vehicles were randomly selected from the 35,000 gasoline vehicles in the 2019 telematics data, and the selected vehicles were clustered into ten types of EV clusters. Figure 12 shows the total trip distance data for each cluster and each time of day. Figure 13 shows the ratio of the vehicles parked at home. Further, as a method to estimate the consequential charging power (charging immediately after arriving at home), a map showing the relationship between the SOC at the time of arrival at home, travel distance of the next trip, and plug-in probability (Figure 14) was created using the telematics data of EVs from January to December 2019. The data were gathered for each of the ten types of EV clusters described above for creating the time-series data of the charge power for the EV clusters.

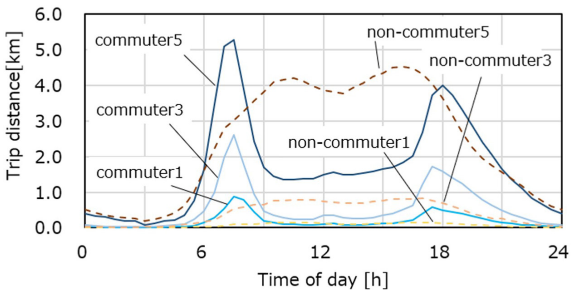

Fig. 12 Trip distance data for each time of day

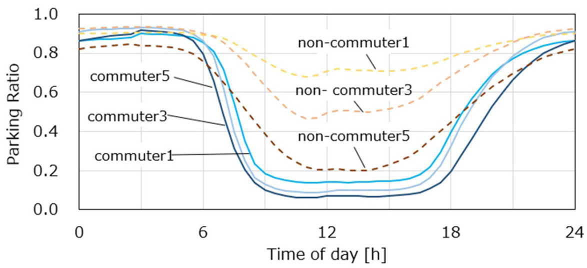

Fig. 13 Ratio of parking at home for each time of day

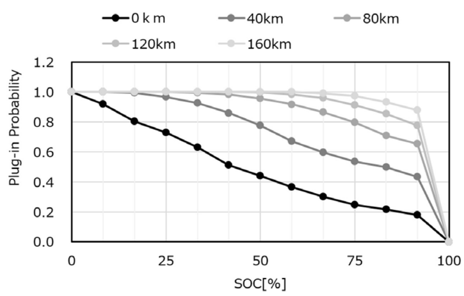

Fig. 14 Plug-in probability with respect to the trip distance of the next trip

3.3 Results
3.3.1 Results of simulating the power supply and demand

An optimization calculation was conducted for a 1-year period using the prerequisites described above to simulate the power supply and demand. As an example, the power supply and demand for August 1 are shown in Figure 15. The maximum power demand on this day was 17.2 GW. A significant amount of power was generated by REs on this day. The output of the thermal power generation was lowered to the minimum limit because the output from REs increases during daytime. In the evening, the output from the thermal power generation increased with a decrease in the amount of power generated from the REs. Further, the optimization calculation results indicate that the calculation was performed to in it can be seen that crease the output from the pumping-up hydraulic power generation and suppress the output from the thermal power generation when ramping up the thermal power generation in the evening. Using this day as reference, optimization calculations were performed for each EV scenario, and the results are presented in Figure 16, which illustrate the total power charged to and discharged from the EVs. The peak of "(i) consequential charging" was 0.1 GW, which is a small amount compared to the maximum electricity demand. However, the peak overlapped with the peak of thermal power generation after 18:00. In contrast, in "(ii) management implemented for charging," the charging time increased during the daytime (i.e., the hours when the amount of power generated by REs is large) and decreased in the evening. In addition, in "(iii) management implemented for charging and discharging," the calculation results showed that charging increased during the daytime and the charged electricity discharged in the evening.

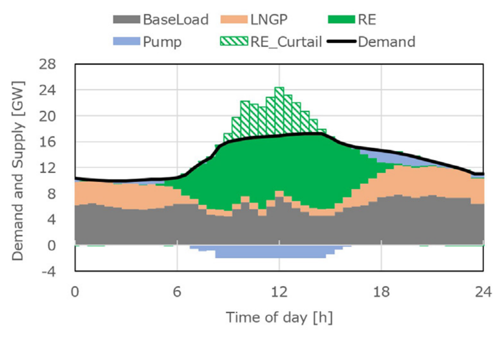

Fig. 15 Example of the hypothetical power supply and demand used in the simulation (considered as August 1)

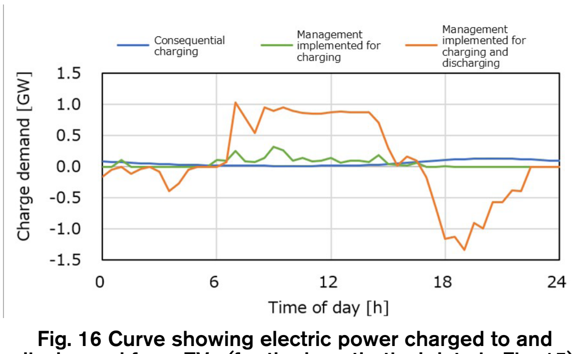

Fig. 16 Curve showing electric power charged to and discharged from EVs (for the hypothetical data in Fig. 15)

The charge power for each EV cluster is shown in Figure 17 for the scenario "management implemented for charging," and in Figure 18, for the scenario "management implemented for charging and discharging" (only six out of the ten clusters are shown in the figures).

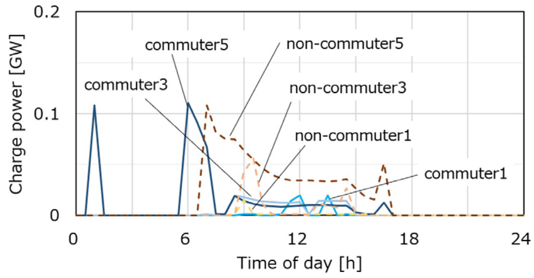

Fig. 17 Time-series data of power demand for each cluster for the scenario "management implemented for charging"

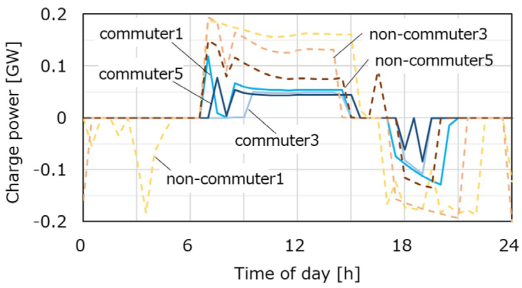

Fig. 18 Time-series data of power supply and demand for the scenario "management implemented for charging and discharging"

3.3.2 Results of evaluating the amount of CO_2 emissions

Table 2 shows the calculation results for the operational costs of the thermal power generator and CO_2 emissions for each scenario. The results indicate that the CO_2 emission amount was 7.5 Mton-CO_2/year for consequential charging. A reduction of 0.3 Mton-CO_2/year was anticipated for "management implemented for charging," and a reduction of 0.7 Mton-CO_2/year was anticipated for "management implemented for charging and discharging." A reduction of 0.9 ton-CO_2/year was anticipated for "management implemented for charging" when the results were converted to the amount of reduction in CO_2 emissions for a single EV vehicle, and a reduction of 1.9 ton-CO_2/year was anticipated for "management implemented for charging and discharging."

Table 2 Simulation results for each scenario

	Operation cost [billion yen]		CO2 emission [Mton-CO_2]	
w/o Control	165.1	(-)	7.5	(-)
w/ V1G	160.4	(-4.7)	7.2	(-0.3)
w/ V2G	151.9	(-10.2)	6.8	(-0.7)

Although omitted in this article, the literature(10) shown in the References simultaneously performed a quantitative evaluation of battery degradation caused by this VGI at the same time. Please refer to the literature for references.

4. Co-creation activities with local communities and with other industries

Although EVs are innovations in mobility, as described above, they also have a significantly large effect on the social systems of the future, especially on the electric power systems. The impact is expected to be either positive or negative depending on how we respond.

Therefore, as an EV manufacturer, there is a responsibility to direct the impact in a positive direction. Given this context, Nissan has exchanged opinions regarding VGI implementation with many members of local governments and private companies. Among these efforts, this section introduces a case example performed in the Aizu, Kitakata area of Fukushima Prefecture. Co-creation activities with the local government and private companies demonstrated a new energy management system that includes a combination of the charge/discharge management of EVs and on-demand control of air conditioners. Figure 19 shows the four charge-and-discharge units installed at Matsumoto Precision Inc. and the company vehicle of the customer (ARIYA)

Fig. 19 Demonstration of VGI (Matsumoto Precision Inc. located in Kitakata City, Fukushima Prefecture)

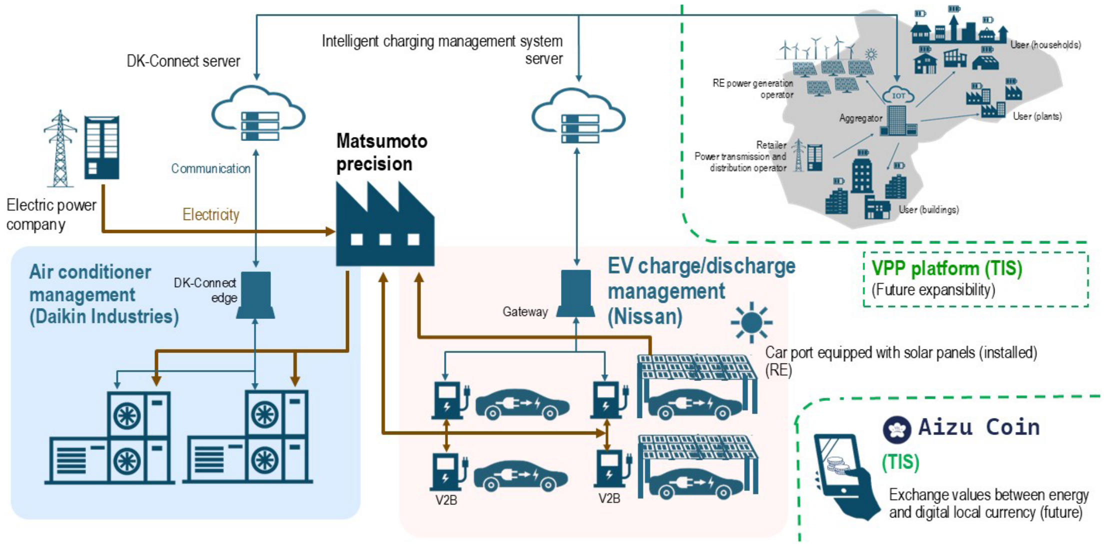

Fig. 20 Conceptual illustration showing the practical application verification of the energy management system where EVs and business-use air conditioners are cooperating (jointly conducted by Nissan Motor Co., Ltd.; Daikin Industries, Ltd.; TIS Inc.; and Matsumoto Precision Inc.)

Figure 20 shows a conceptual illustration of an energy management system that started from December 2023(16). This system automatically determines the charging/discharging output of EVs owned by the company and employees and automatically performs charging/discharging considering the SOC of each EV at the relevant time and the next time each vehicle is used to ensure that its usefulness as a mobility vehicle is not impaired. In addition, the system cooperates with business-use air conditioners made by Daikin Industries, Ltd. to reduce electricity costs and contribute to the consumption of locally generated energy while maintaining comfort in the workplace. The goal of this activity is not limited to delivering value to one of our customers but also, to increasing the number of buildings with similar flexibility in electricity demand in future and having the buildings become connected to improve the economic efficiency of REs in the entire region and accelerate widespread use. Further experiments are planned to achieve this goal. For example, there are future plans led by TIS Inc. to develop this activity into a VPP*1 and establish an incentive system, i.e., the introduction of a local currency "Aizu Coin," for encouraging EV users in the area to proactively join the activity (Figure 20, right side).

These types of activities are completely new, and therefore, most members of the local governments and customer companies have no information about "What should be done, what kind of value is created, and what are the conditions for obtaining that value?" In such a scenario, it is difficult to decide whether to introduce this system. Therefore, sharing the vision and values with our customers and partner companies as well as holding continuous discussions to mutually confirm the direction and issues of the activities is necessary to ensure that the activity ultimately becomes specific and introduces a win-win scenario for both parties. It is believed that the introduction of VGI will spread through continued activities as described above.

5. Conclusion

Energy management utilizing EVs (VGI) can be considered a necessary system in a future society, and this requires realizing the mass adoption of REs. However, it may take more time for the use of EVs to become widespread and for an ecosystem to be established wherein the business of all stakeholders becomes feasible. Therefore, communicating the values of VGI in a simple language and quantitatively demonstrating the material effects by introducing VGI is necessary. Thus, introduction cases are expected to increase, which can lead to lower costs for the charge and discharge units and a reduction in installation costs. In addition, there are expectations that, owing to advancements in vehicle connectivity, energy management can be realized efficiently, in a wide range, and with a large number of EVs. To realize this future, Nissan will continue its efforts to achieve widespread adoption through further technological developments and by performing demonstrations to verify the social effects of such developments.

Terminology

*1 VPP: Virtual Power Plant. The system uses Internet of Things to virtually connect the distributed energy resources to balance the supply and demand of electric power.

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Authors

Keigo Ikezoe

7. Commercializing used EV Battery Reuse

Yutaka Horie*

1. Introduction

Automotive electrification is being pursued to help achieve carbon neutrality by 2050, a critical step in realizing a sustainable society. As more electric vehicles (EVs) are produced and used, more batteries will be in circulation. However, batteries contain many valuable materials that can be recycled and reused to realize a low-carbon society and reduce the use of virgin resources. The 4R Energy Corporation was established in September 2010 in Japan before the launch of the first-generation Nissan LEAF EV to ensure the effective reuse of lithium-ion battery (LiB) materials. The company launched its Namie office in 2018 and began a full-scale business to reuse, refabricate, and resell LEAF LiBs returning from the EV market in Japan.

2. What is a 4R business?

As shown in Figure 1, the “4R” in 4R Energy stands for reuse, refabrication, resell, and recycling. Reuse involves reutilizing recovered LiBs in pack form. Refabrication involves the disassembly of battery packs into modules to fabricate new packs with different voltages and capacities as necessary to meet client requirements. Resell provides used LiBs to the market for various uses, including renewable energy and backup power storage. Finally, recycling recovers the materials in used LiBs for use in new LiBs for other applications. The 4R Energy Corporation is one of the few companies in the world that has built a business from used EV batteries and is currently a pioneer in the LiB reuse/repurposing industry with 14 years of experience.

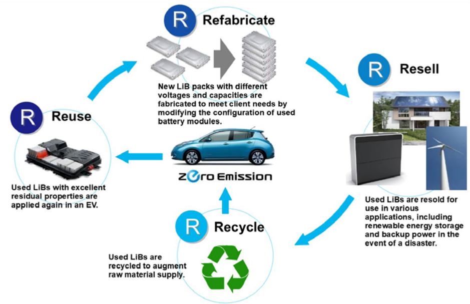

Figure 1 What is a 4R business?

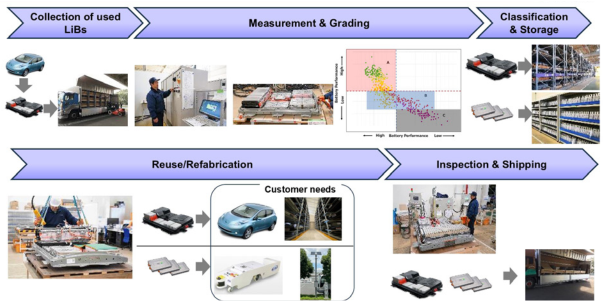

Figure 2 Reuse and refabrication process

2.1 Reuse and refabrication of used LiBs for Japan market

Figure 2 illustrates the process of reusing and refabricating used LiBs. First, used LiBs are collected from Nissan dealers and vehicle disposal companies nationwide and then cleaned and inspected. Battery packs that pass this receiving inspection are subjected to tests analyzing the performance of all modules and cells within, and the resulting data are stored in the management system. The analyzed LiBs are graded according to their deterioration levels and stored as packs or modules in specified racks to await selection based on customer requirements.

Prior to shipment, LiB packs are disassembled to replace their modules as required, then reassembled; their battery control programs are rewritten for the customer-specified reuse purpose; finally, pack functions such as relay control and sensors are evaluated. Modules with the customer-required performance grade are collected by disassembling packs or retrieval from storage and then placed in a special casing for shipment.

*4R Energy Corporation

3. Reusing LiBs

3.1 Benefits of LiB reuse

Reusing LiBs has four benefits:

(1) The increased value of LiBs increases the residual value of EVs, contributing to sales growth.

(2) The use of end-of-life LiBs for energy storage increases the use of renewable energy by providing highly competitive Energy Storage System costs.

(3) The effective utilization of valuable metals such as lithium, cobalt, nickel, and graphite through recovery and reuse alleviates resource constraints. Once LiBs have aged out of use in EVs and have been reused and repurposed to the extent possible, these valuable metals can be extracted from them and recycled instead of discarded (Figure 3). These recycled materials can be returned to the manufacturing process, where they can reduce the costs and carbon dioxide (CO_2) emissions associated with the production of LiBs for new EVs.

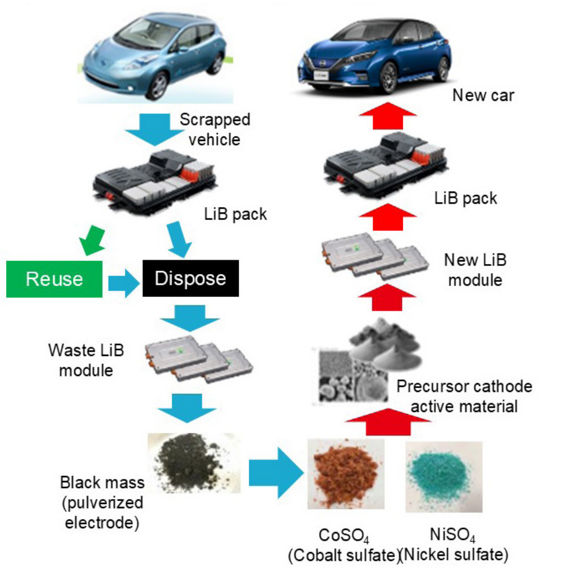

Figure 3 Recycling of battery materials

(4) The use of recycled materials reduces approximately 6.2 tons of CO_2 emitted during the production of a single EV LiB—equivalent to the quantity of CO_2 emitted by 3.23 people in a year—by up to 93%, as demonstrated by 4R Energy (Figure 4). Indeed, LiB recycling is characterized by its ability to reduce CO_2 emissions in different stages of the battery life cycle, including resource mining, raw material production, and LiB production.

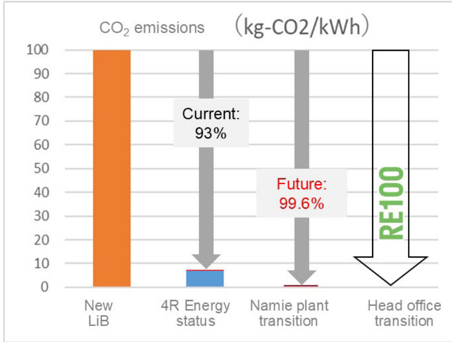

Figure 4 Reduction of CO_2 emissions during LiB production

3.2 Key considerations for LiB reuse

Two key considerations dictating LiB reuse are performance and safety. In terms of performance, technologies have been developed to accurately measure the degree of LiB performance degradation at the time of collection and estimate the degradation characteristics after resale. These technologies are intended to address the negative impression of many customers regarding recycled batteries as being degraded and unusable, assigning used LiBs to suitable products based on their measured performance and allowing for the reuse of even the lowest-performing LiBs (Figure 5).

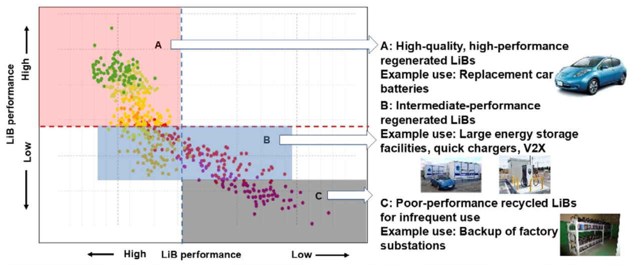

Figure 5 LiB reuses according to degradation state

In terms of safety, a fourfold safety assurance philosophy is employed to address the concerns of customers who fear the potential danger of used LiBs. This philosophy comprises assertions that:

(1) Only Nissan LEAF batteries, which are safe, reliable, and durable, are used; Nissan has sold more than 670,000 LEAFs.

(2) All batteries are UL1974 certified, indicating that an international certification organization has endorsed 4R Energy's battery reuse process as safe.

(3) All batteries adopt the safety concepts and control logic applied in the Nissan LEAF to ensure the same safety and reliability as the vehicle.

(4) Recycled battery packs are stored in an explosion-proof enclosure designed considering the possibility of accidents or in a cubicle certified by the relevant fire prevention ordinance.

3.3 Example LiB reuses

The demand for LiBs is increasing for many reasons, including efforts to achieve carbon neutrality by 2050, increased business continuity planning demand owing to frequent disasters, and the expansion of renewable energy to address power shortages and soaring electricity costs. Indeed, the use of large-scale battery storage in the Grid-power-conditioning market has expanded considerably in recent years. Given this multitude of applications, a wide range of storage batteries have been made available in various sizes for applications ranging from large energy storage systems (ESSs) to Off-grid street lighting, as shown in Figure 6.

Figure 6 Reuse cases for used LiBs

When LiBs exhibit relatively little deterioration at the time of collection, they can be reused as replacement batteries for LEAF vehicles. Those with considerable deterioration to disqualify as replacement batteries for LEAF vehicles can be used in large ESSs, such as the battery station at the Namie plant (Figure 7). This ESS stores power generated by solar panels installed on the roof of Namie plant, providing a total capacity equivalent to 84 LEAF EVs. A demonstration experiment has confirmed that using 100% renewable energy stored at the plant site is feasible if rain or cloud cover is absent for at least three consecutive days.

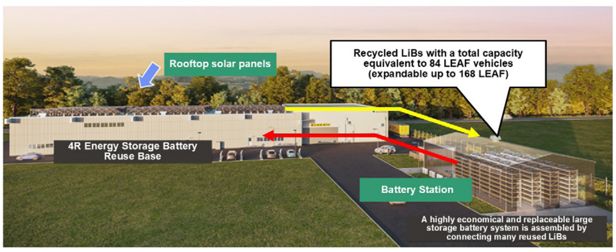

Figure 7 Battery station at the Namie plant

A backup power supply for grade-crossing protection systems was developed in cooperation with the East Japan Railway Company. These systems were first installed in 2022 as replacements for lead–acid batteries at more than 500 locations. These LiB-based backup power supplies will continue to replace lead–acid batteries as the latter reach their replacement times (Figure 8). The lead–acid batteries in the automated guided vehicles operating inside Nissan's plants are also gradually being replaced with reused LEAF LiBs (Figure 9).

Furthermore, reused LEAF LiBs have been applied in portable power supplies (Figure 10) through a partnership with JVC KENWOOD Corporation. After the Noto Peninsula earthquake, Nissan donated 100 portable power supplies and JVC KENWOOD donated 100 solar panels for use at evacuation centers.

Figure 8 Backup power supply for grade-crossing protection systems (lead–acid battery substitute)

Figure 9 Automated guided vehicles used in a Nissan factory

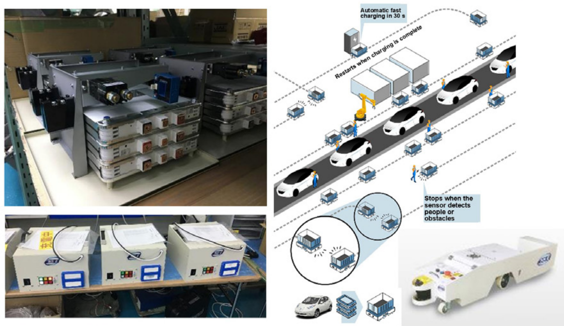

Figure 10 Portable battery containing recycled LEAF LiBs

Finally, Nissan led an initiative to install more than 130 off-grid light-emitting diode (LED) streetlights using recycled LiBs for energy storage. During the day, the solar panels on these lights generate electricity that is stored and subsequently used to power the LEDs at night. These lights can be used for lighting along evacuation routes and in evacuation shelters in the event of a disaster as they are unaffected by power outages. Furthermore, the battery box on the light is removable and equipped with a USB port that can be used to charge cell phones (Figure 11).

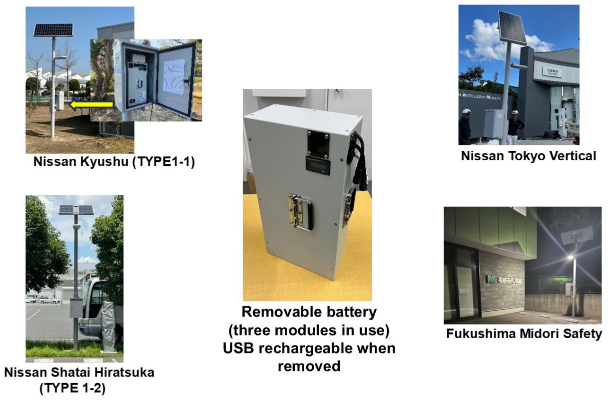

Figure 11 Off-grid streetlights equipped with emergency storage LiBs

4. Challenges and initiatives

Various challenges must be addressed to realize a sustainable business based on the circular LiB economy. For example, systems and services must be established to return EVs and LiBs to Nissan. According to research conducted by the 4R Energy Corporation, approximately 20,000 used EVs will be exported from Japan in 2023, limiting the number of vehicles remaining in the country. A notable reason for the outflow of used EVs from Japan is that the growth of EV utilization is stagnant in Japan owing to concerns regarding battery performance and capacity. Systems and services for limiting the export of used EVs are under consideration accordingly.

In addition, technologies that can quickly and accurately estimate the health of LiBs must be developed and are being actively pursued by Nissan. Furthermore, the efficiency and safety of LiB removal must be improved using designs that allow battery packs to be easily and quickly removed from vehicles and allow battery modules to be removed from packs; these are also being developed by Nissan. Finally, efficient recycling technologies must be developed, and reverse logistics systems established to support strategic recycling considering the requirements for reuse, efficiency, and minimization of CO_2 emissions. Indeed, the market for recycled LiBs can be expanded by creating new value that will attract customers, such as the reduction of carbon footprint.

Although 4R Energy has received tremendous cooperation from the Nissan Group, additional alliances must be forged with other collaborative industries and stakeholders. A joint public-private sector council on the circular LiB economy has been established accordingly.

5. Conclusion

The 4R Energy Corporation is building a business based on the circular LiB economy to help Nissan realize a low-carbon society. These efforts combat climate change while reducing the use of virgin resources through recycling to alleviate resource dependence.

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Authors

Yutaka Horie

8. Innovative Battery Material Recycling Technology

Takehiko Okui*   Tomohiro Mitsuyama*   Atsushi Ohma*

1. Introduction: Social background of lithium-ion battery recycling

The markets for electric vehicles (EVs) and the lithium-ion batteries (LiBs) used within them have expanded rapidly in recent years. Consequently, LiB recycling has attracted increasing attention to address issues associated with environmental protection, regulatory compliance, and resource security.

In terms of environmental protection, used LiBs must be treated properly because they contain materials that can pollute soil and water, such as organic electrolytes and heavy metals. An additional challenge is the need to reduce CO_2 emissions associated with mining and refining the resources used in LiBs.

In terms of regulatory compliance, the European Union Battery Regulation, which came into force in August 2023 and has been applied gradually since February 2024, establishes targets for battery recycling efficiency and metal recovery rates (Article 71), required percentages of recycled materials in active metal materials (Article 8), and obligations to declare the carbon footprint of each battery model and manufacturing plant (Article 7).[1]

In terms of securing resources, various risks are associated with the supply of raw materials owing to the rapid increase in demand for LiBs and the fact that only certain countries can produce these raw materials.

These issues have led to recent efforts to establish closed-loop recycling systems in which used LiBs and manufacturing waste are processed to obtain battery-grade raw materials for new LiBs. This chapter accordingly presents an overview of LiB (particularly direct cathode) recycling technologies being researched and developed at Nissan and details our efforts toward its implementation.

2. Overview of LiB recycling technology

The materials targeted for LiB recycling include cathode active materials and electrolytes primarily containing lithium (Li), bus bars and current-collecting foils made of copper (Cu), and exterior materials for cells, modules, and packs containing steel and aluminum (Al). The most promising materials for recycling are ternary nickel (Ni)–manganese (Mn)–cobalt (Co) (NMC) cathode active materials, which are commonly used in automotive LiBs, including the second-generation Nissan LEAF (released in 2017), owing to the valuable metals within (Figure 1).

The development of technologies for recycling NMC cathode active materials is the focusof this section. As shown in Figure 2, the various process flows involved in recycling such materials can be broadly classified into conventional recycling processes, which have recently begun to see practical use, and direct recycling processes, which remain in the research and development stage. Outlines of these processes are provided below.

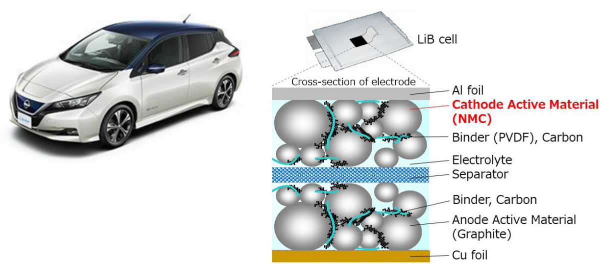

Figure 1 Schematic of the electrode structure in the LiB of a second-generation Nissan LEAF

2.1 Conventional cathode recycling

Conventional cathode recycling extracts metals (or metal compounds) from powders containing cathode active materials (black mass) which is recovered by mechanical process, or alloys and metal oxides recovered by pyrometallurgical process. Impurities in recovered metals can be removed through hydrometallurgical process such as leaching, solvent extraction, precipitation, crystallization[2]. A flowchart of a typical conventional cathode recycling process is shown in Figure 2. Various technologies can be used in such processes and differ according to the recycling company. The following process steps are typical.

During preprocessing, LiBs are discharged and

*EV System Laboratory

disassembled into modules or cells. The disassembled LiBs are calcined (in some cases) and subsequently crushed, separated, and classified to produce a black mass that can be separated into specific materials using dry or wet processes. Notably, the calcination process vaporizes the electrolyte to suppress ignition during crushing and thermally decomposes the resin materials to facilitate separation, though in some cases, LiBs are crushed in an inert gas atmosphere without undergoing calcination.

In dry processes, LiB modules or cells are fed into a furnace at over 1000 °C where their non-metallic materials are burned off and only metals are recovered. Cu, Ni, and Co are highly reducible and can be recovered as alloys, whereas Li and other metals become mixed oxides (slag). Notably, the recovered alloys can be refined using a simplified wet process because of their low impurity contents. Therefore, the black mass is sometimes treated using a dry process, followed by a wet process.

Wet processes leach the metals from a pretreated black mass or the alloys obtained by a dry process using an aqueous acid or alkali solution. Each metal ion is separated into organic solvent and aqueous phases by adding an organic solvent and extractant into the leaching solution and adjusting the temperature and pH (solvent extraction). Separated metal ions are synthesized into compounds such as nickel sulfate ($NiSO_4$) and cobalt sulfate ($CoSO_4$) after undergoing further processing to remove impurities. These compounds are subsequently used as raw materials in new NMC cathodes. Recently, some recycling companies have extracted metals simultaneously without separation and refined them into a high-purity Ni, Co and Mn mixed aqueous solution that can be used as a raw material for cathodes.

Challenges confronted by conventional recycling methods include the high costs associated with multiple processes, long processing times, and high CO_2 footprints. Furthermore, the hydrogen fluoride gas generated by the thermal decomposition of the electrolyte and binder during the pretreatment and dry processes must be detoxified, and the large quantities of acidic and alkaline chemicals consumed by leaching and pH adjustment in wet processes generate a large volume of wastewater that must be treated[(3)]. Finally, the production of battery-grade LiB raw materials using a wet process requires lengthy, multiple-step solvent extraction that necessitates considerable capital investment.

Conventional recycling technologies remain under development as various advances have been made in recent years, including the development of new extractants and improvements in the recycling rate realized using advanced Li recovery from slag after pyrometallurgical process[(3)]. However, conventional recycling does not yet provide cost or CO_2-emission advantages over the mining and refining of virgin materials, and its profitability remains highly dependent on the prices of Li, Ni, and Co.

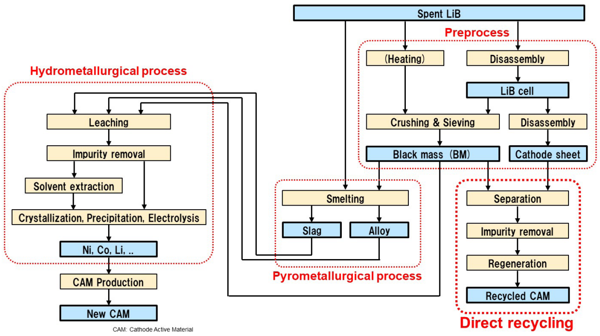

Figure 2 Example process flow for LiB cathode active material recycling

2.2 Direct cathode recycling

Direct recycling separates and recovers cathode active materials while maintaining their original structures; after impurities are removed, these materials can be regenerated and reused in new LiB cathodes. Direct recycling can avoid the cathode manufacturing process from recycled materials. Manufacturing process for cathode active material includes chemical synthesis and heat treatment shown in Figure 3, and consumes much chemical and energy. Therefore, the direct recycling method has attracted attention for realizing low-cost, low-CO_2 emissions closed-loop recycling.

Research and development of direct recycling is being conducted by various research institutes, LiB manufacturers, and recycling companies[(3)]. Various methods can be used to achieve direct recycling; an example of the direct recycling process being developed by Nissan is described in this section. This process, shown in Figure 4, comprises four steps:

(1) pretreatment to separate the cathode sheets from the LiBs,
(2) separation of the cathode active material from the cathode sheets,
(3) removal of residual impurities from the cathode active material,
(4) regeneration of the cathode active material.

2.2.1 Pretreatment

Heating process is generally avoided during pretreatment to prevent the degradation of the cathode active material by thermal decomposition or the generation of hydrogen fluoride. Acceptable pretreatment methods include the removal of cathode sheets by manually disassembling LiB cells and the separation and recovery of cathode sheets by crushing LiB modules or cells in water or an inert gas atmosphere. Crushing is better suited to industrial processing as the subsequent physical sorting methods, such as specific gravity, magnetic, and forced-air processes, are relatively cheap and easy to implement.

2.2.2 Separation of cathode active material

The separation of cathode active material from the Al current collector is accomplished by dissolving a polyvinylidene difluoride (PVDF) binder in an organic solvent such as N-methyl-2-pyrrolidone (NMP). the cathode active material powder is stripped from current collector by immersing in NMP, heating and agitation, and then via solid–liquid separation. Notably, the spent NMP can be purified by distillation or other methods for reuse. As NMP is already used in industrial LiB production, its recovery can be achieved through an established supply chain.

2.2.3 Removal of residual impurities

Cathode active materials recovered through the direct recycling pretreatment and separation processes contain impurities originating from the processing equipment and LiB cell components. These impurities primarily comprise minute fragments of Cu and Al from the current-collector foil, graphite from the anode active material, residual PVDF and conductivity aid (carbon) in the cathode. these impurities can have negative effects on cathode active material and LiB cells (Table 1).

For example, when cathode active material containing residual PVDF is subjected to post-processing heat treatment, hydrogen fluoride (HF) is generated by the thermal decomposition of PVDF. HF reacts with Li and oxygen (O) in the cathode active material, and form lithium fluoride impurities on the active material surface or changes the crystal structure of cathode active material[4]. Furthermore, metal impurities such as Cu can cause an internal short circuit Therefore, impurity removal is inevitable process for closed-loop recycling.

Several methods have been developed to remove such impurities and recover highly pure cathode active materials. Flotation can be used to separate carbonby trapping hydrophobic C particles in bubbles suspended by surfactants, underwater agitation, and bubbling, then separating the hydrophilic cathode active material particles that settle to the bottom of the water[5]. This technique has been previously applied in the mining industry.

acids are unsuitable for direct recycling because they dissolve active cathode materials. Therefore, metal impurities such as Cu and Al can be dissolved and removed using alkaline solutions. Ammonia is well-suited to the dissolution of Cu, and strong alkaline solutions such as lithium hydroxide (LiOH) can be used to dissolve Al.

Hydrothermal treatment can be used to remove PVDF impurities by immersing the recovered cathode active material in an aqueous alkaline solution, then pressurizing and heating it in an autoclave. This decomposes and transforms the PVDF into water-soluble substances, such as fluoride ions. Notably, a highly concentrated LiOH solution can concurrently replenish any deteriorated Li in the cathode active material.

These applications of alkaline chemicals to remove Cu, Al, and PVDF can leave less than 1 wt.% of these impurities while minimizing the consumption of chemicals in the reaction. Therefore, the selection of optimal process parameters and establishment of processes for the purification and reuse of spent alkaline solutions can result in an inexpensive industrial process with a low environmental impact.

2.2.4 Regeneration of cathode active material

The degradation states of cathode active materials vary depending on the usage history of the LiBs from which they were obtained. Such materials may not only exhibit Li degradation but also changes in their surface crystal structures and cracking[4]. This degradation can be repaired to a considerable extent by heat treatment under conditions similar to those used in the production of new cathode active materials.

A series of lab-scale experiments (Figure 5) confirmed that the charge–discharge characteristics of directly recycled NMC cathode active materials obtained from used LEAF LiBs (Figure 5, "After regeneration") were nearly identical to those of unused NMC cathode active materials (Figure 5, "Pristine"). Future work by 4R Energy will continue to develop technologies establishing new processing methods and conditions for regenerating cathode active materials in various states of degradation.

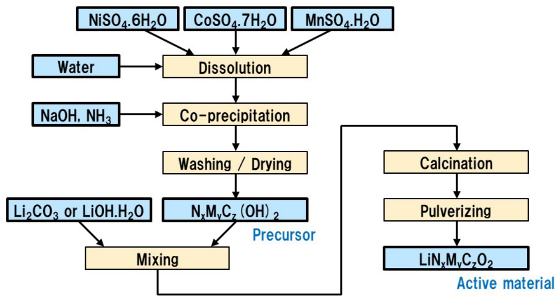

Figure 3 Example NMC cathode active material production process using conventional recycling

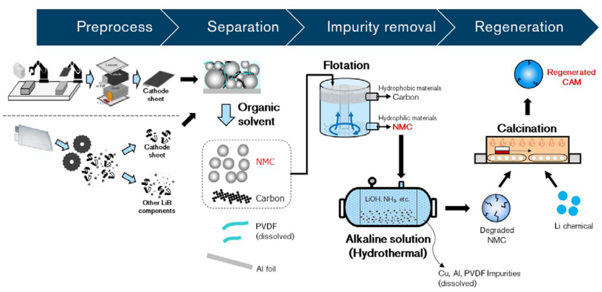

Figure 4 Example of direct cathode recycling process

Table 1 Major impurities and their effects on direct cathode recycling

Impurity	Source of impurity	Influences on NMC and LiB
PVDF	Cathode binder	Changing crystal structure of NMC Forming surface impurity on NMC $(CH_2CF_2)n + 2nO_2 \rightarrow 2nHF + 2nCO_2$ $2LiMO_2 + 2HF \rightarrow 2LiMO_{1.5}F + H_2O$ $4LiMO_2 + 4HF + O_2 \rightarrow 4MO_2 + 4LiF + 2H_2O$ (M : $Ni_yCo_zMn_{1-y-z}$)
Carbon (Graphite)	Cathode conductive additive Anode active material	Changing crystal structure of NMC (by reducing transition metals during calcination)
Fe (Steel)	LiB cell casing Process equipment	Changing crystal structure of NMC (due to incorporation into NMC) Internal short-circuit in LiB cell
Cu	Anode current collector	
Al	Cathode current collector	

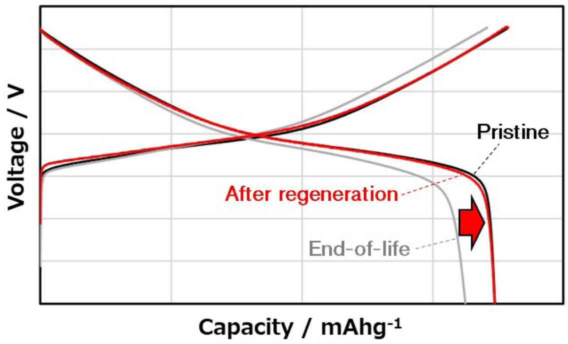

Figure 5 Charge–discharge characteristics of recycled cathode active material

3. Benefits and challenges of direct cathode recycling

The CO_2 footprint of the regenerated NMC cathode active material recovered by 4R Energy's direct recycling process (Figure 4) was estimated from the raw material extraction to the manufacturing stages. The carbon footprint of the directly recycled cathode active material (Figure 6, "Direct recycling") is expected to be 75% lower than that recycled conventionally (Figure 6, "Conventional recycling"). However, this is an estimation as the CO_2 footprints of materials obtained by conventional recycling are difficult to determine authoritatively, owing to the availability of various recycling methods. Nevertheless, the conventional recycling process clearly has no CO_2 emissions advantage over the manufacture of cathode active materials using virgin resources obtained through mining and refining (Figure 6, "Pristine"). Critically, direct recycling does not require the production of any new cathode active material. Therefore, the direct recycling technology developed by 4R Energy exhibits a clear advantage in terms of the CO_2 footprint over the manufacture of cathode active materials from virgin resources or conventionally recycled materials.

The NMC cathode active material accounts for a significant portion (approximately 30%–40%) of the CO_2 footprint of an LiB, depending on the analysis[6]. An LiB containing 20% recycled cathode active material obtained by the 4R Energy direct recycling method yields a 15% lower CO_2 footprint for the cathode active material and a 5%–6% lower CO_2 footprint for the LiB, representing a 75% reduction compared to that realized by a conventional recycling process.

Although the cost of procuring used LiBs and capital investment required to establish direct recycling must be carefully examined in the future, recycled cathode active materials can likely be produced at approximately half the cost of virgin cathode active materials.

Many technical issues remain to be solved before the benefits of direct cathode recycling can be realized. These generally include:

(1) ensuring that recycled cathode active materials have the same properties as virgin cathode active materials in terms of charge–discharge capacity as well as other properties such as input–output characteristics, durability, and safety,
(2) establishing optimal recycling process conditions according to the various degradation states of used LiBs,
(3) adapting each process to the industrial scale,
(4) establishing a manufacturing method that ensures the quality of LiBs containing recycled cathode active materials.

4R Energy intends to first develop technologies addressing issues (1) and (2) in the lab, then scale these processes to address issues (3) and (4).

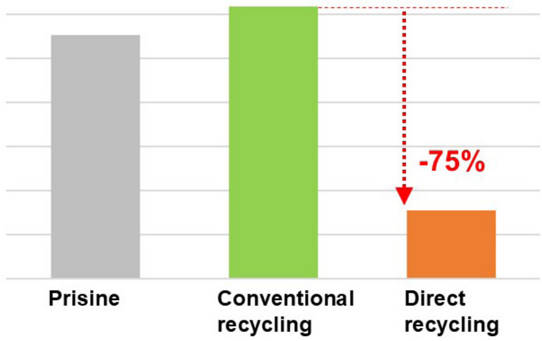

Figure 6 Carbon footprint of NMC cathode active material production from the raw material extraction to manufacturing stages

4. Implementation of direct cathode recycling

Efforts are underway to establish technologies for recycling cathode active materials into new LiBs for EVs. A concept resource recycling system has been developed to inform efforts to achieve this goal, as shown in Figure 7, and a series of supply chains are under construction accordingly.

The secondary use of LiBs has already been commercialized by 4R Energy to classify them for reuse (in vehicle LiBs), repurposing (reuse for other applications), or recycling according to their state of degradation. In addition to these efforts, the concept resource recycling system shown in Figure 7 nondestructively estimates the degradation state of the cathode using the LiB performance measurements and usage history to classify it as suitable for either direct recycling or conventional recycling (recovery of metal raw materials). The LiBs classified as suitable for direct recycling will undergo separation and regeneration of the cathode active material for use in the production of new LiBs.

As these processes require new technologies and quality assurance practices, partnerships among LiB recycling companies, cathode active material manufacturers, and LiB manufacturers are required to integrate direct recycling technology into resource recycling systems. In addition, because direct cathode recycling technology involves processes considerably different from conventional LiB recycling processes, partnerships with industries beyond conventional recycling may be advantageous. In the future, 4R Energy intends to recruit partners familiar with the necessary technologies for each process in the concept resource recycling system to promote cooperative efforts.

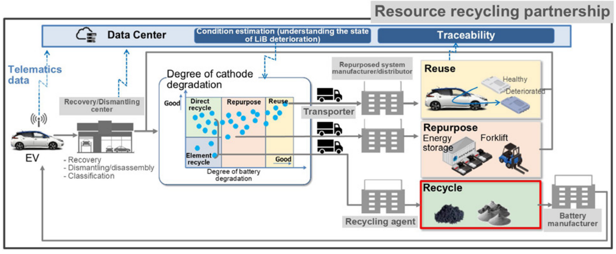

Figure 7 Concept LiB resource recycling system

5. Conclusion

The rapid expansion of the EV market has focused significant attention on LiB recycling in recent years. However, as many automobile manufacturers have no prior experience with such technologies, partnerships with recycling companies are essential for translating LiB recycling concepts into businesses.

In this manner, 4R Energy will continue its efforts to help realize a society with sustainable mobility through the implementation of innovative recycling technologies.

Acknowledgments

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