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ADVANCE

Innovation of New Mobility Infrastructure towards Sustainable Society

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Changes for the Better

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Mitsubishi Electric ADVANCE

Innovation of New Mobility Infrastructure towards Sustainable Society

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Mitsubishi Electric Corporation is advancing a range of transformation initiatives to achieve DX (Digital Transformation) and GX (Green Transformation), with the aim of creating safe and environmentally friendly mobility infrastructure for all. This issue features the Railway Energy Management Solution (EMS), which uses "Serendie," as a DX-related topic, along with the next-generation battery module "MHPB" and railway air-conditioning systems using the natural refrigerant R290 as GX-related topics.

Foreword

Author: *Fujio Toriumi**

** Professor, the University of Tokyo*

The Greatest Risk of AI is Ignoring it

The overall image of artificial intelligence technologies is difficult to grasp, and partly because the technologies considered central to AI change over time. Ten years ago, deep learning itself was often regarded as synonymous with AI, but today the term is more commonly associated with generative AI tools such as ChatGPT. In reality, however, AI includes a much broader range of technologies. It can be applied to prediction, recognition/estimation, generation, analysis, design, and collaboration. AI systems that process large volumes of data are particularly well suited to industrial applications. For example, demand forecasting based on large volumes of data and product design using deep learning may have more use cases than generative AI. Image recognition and related technologies are also in high demand at manufacturing sites.

Survey results indicate that the use of artificial intelligence technologies is lagging in Japan. This may reflect caution about the risks of using new technologies. However, technological innovation is now advancing so rapidly that failing to adopt new technologies can itself become a significant risk.

Naturally, introducing new technologies may seem to require enormous costs. Yet universities, as an example, are constantly researching and developing the latest technologies and seeking applications for them. Companies that introduce AI in collaboration with university laboratories may therefore gain access to advanced expertise while creating mutually beneficial partnerships between industry and academia.

Future Vision of Railway EMS with "Serendie"

Authors: *Yasutaka Imamura*, Kosuke Shinji***

**Itami Works, ** Kobe Works*

Abstract

Mitsubishi Electric Corporation is leveraging its proprietary digital platform "Serendie" to advance comprehensive optimization of energy operations for railway systems by beginning with providing data analysis services, as well as introducing optimal placement and optimal control of railway operator assets, controlling train operations for multiple trainsets, and further integrating these initiatives to maximize their benefits. Data from railway systems will be analyzed and utilized in the future, and collaboration with communities along railway corridors will enable optimization of energy supply throughout the entire region. The deployment of this series of Railway Energy Management Solutions (EMS) will contribute to achieving carbon neutrality.

1. Introduction

Global warming is a major social issue which must be addressed urgently. Reports by the Intergovernmental Panel on Climate Change project serious impacts on the global environment into the future, such as extreme weather and rising sea levels, due to the increasing average temperature on the planet. Accordingly, the Paris Agreement adopted in 2015 established an international framework for measures to combat global warming, and efforts toward achieving carbon neutrality are accelerating worldwide.

In the energy sector, expanding the use of renewable energy sources such as photovoltaics (PV) and improving energy efficiency are key pillars. Initiatives are also underway in the railway industry toward achieving carbon neutrality, including the use of renewable energy and the introduction of eco-friendly rolling stock. To accelerate these efforts, it is also effective to utilize various operational data related to railways, such as operational information, and optimize energy use across the entire line by coordinating railway assets at electrical substations and railway stations with train operations (Fig. 1).

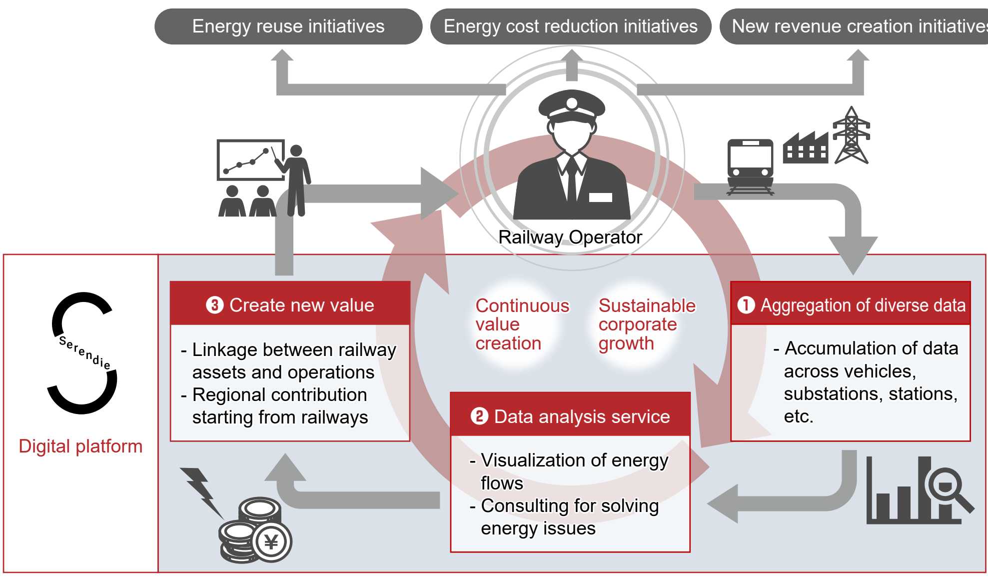


Fig. 1 System diagram of the Railway Data Analysis Service

This paper presents a vision for deploying solutions that contribute to energy optimization across all railway lines and to the optimization of communities along them, starting with data analytics services.

2. Data Analysis of Railway Systems Using Serendie

We have long been working on data analysis and optimization in the railway sector using rolling stock data. An example of this is optimizing the design of control equipment and control parameters using data acquired from rolling stock in operation—we have achieved energy savings such as improving the efficiency of onboard electrical equipment and increasing the amount of regenerative power generated during braking(1).

However, to further achieve carbon neutrality, conventional individual optimization has limitations, and optimizing energy operations across the entire railway system is desirable. Therefore, as the first step, we launched the "Railway Data Analysis Service," which proposes overall optimization by rapidly analyzing operational data for railway systems (including rolling stock data, substation data, station power usage, and the status of train operations) using the digital platform Serendie (Fig. 2).

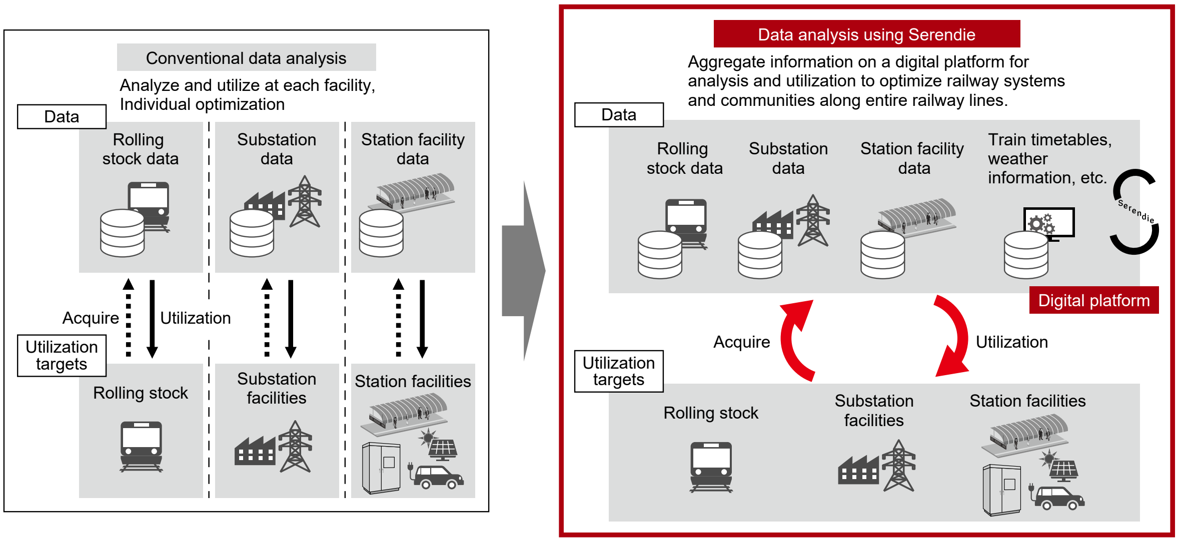


Fig. 2 Conceptual diagram of Railway Data Analysis Service with Serendie

The Railway Data Analysis Service enables analyses that contribute to optimization for the entire railway system; for example, by combining data from multiple rolling stock classes, it can quantitatively identify actual wasted energy across the entire power system. For issues specific to railway operators, the service is able to propose appropriate locations for railway assets such as station energy saving inverters (S-EIV), which are energy-saving equipment that absorb surplus regenerative electric power for use in the railway station, and to propose optimal operational methods for railway assets according to station congestion levels, train timetables, and operational status.

3. Optimization of Railway Systems

Utilizing data analysis, optimal placement and control of railway assets, as well as energy-efficient train operation, can significantly improve efficiency and further reduce the carbon footprint of a railway system.

3.1 Optimal placement of assets

To effectively utilize regenerative electric power, it is important to identify the locations of ground-based facilities and areas where surplus regenerative electric power is generated. To this end, we visualized surplus regenerative electric power using data. Figures 3 and 4 show examples of the analysis of surplus regenerative electric power. In Fig. 3 and 4, the surplus regenerative electric power being concentrated at Stations A and D can be confirmed visually. When surplus regenerative electric power is concentrated at specific points, the installation of ground-based energy-saving equipment at those locations can be effective. By implementing localized measures such as installing an S-EIV which transfers surplus regenerative electric power from rolling stock to ground facilities, and installing energy storage systems that absorb and reuse surplus regenerative electric power, improvements in power consumption can be expected.

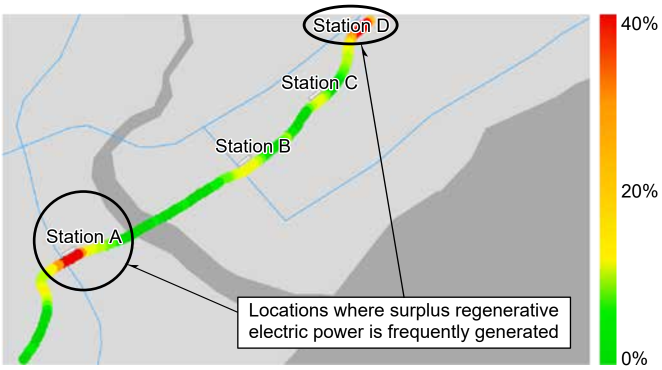
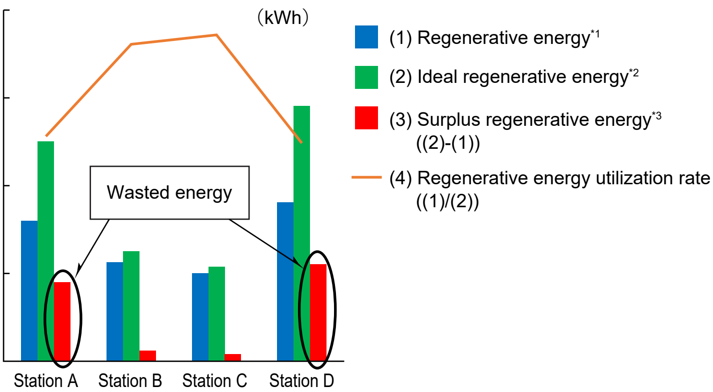


Fig. 3 Geographic mapping of surplus regenerative electric power



*1 Indicates the amount of regenerative electric power that was actually made available to other rolling stock, etc.
*2 Regenerative energy in the case where all braking energy could be converted into electric power
*3 Regenerative energy that is converted into thermal energy by air brakes, etc., and is not being effectively utilized

Fig. 4 Analytical schematic of regenerative energy

3.2 Feeder voltage control for substations

As a further energy-saving measure using existing facilities, we are currently advancing studies on optimal feeder voltage control.

In general, railway traffic density varies depending on the time of day, such as peak and off-peak service schedules. Train density is low during off-peak hours, and regenerative electric power returned to the overhead line during braking cannot be sufficiently shared among powered rolling stock, resulting in frequent regenerative power suppression that limits regenerative electric power output. Because the supply distance of regenerative electric power becomes longer as feeder voltage decreases, lowering the substation feeder voltage is expected to further increase the amount of regenerative power made available. On the other hand, train density is high during rush hours, so regenerative electric power is shared between rolling stock and regenerative power suppression decreases. In such situations, setting the substation feeder voltage higher can reduce losses in substations and overhead lines, and improve the efficiency of onboard traction inverters and motors.

Therefore, it is effective to adjust and optimize the substation feeder voltage by time of day as shown in Fig. 5. However, current substation facilities are not designed on the premise of changing feeder voltage by time of day, and they output feeder voltage at a fixed voltage ratio relative to the receiving voltage throughout the day. In addition, given that the facility capacity, number of units, and supply distance differ by substation, it is ideal to identify and apply the optimal feeder voltage for each substation.

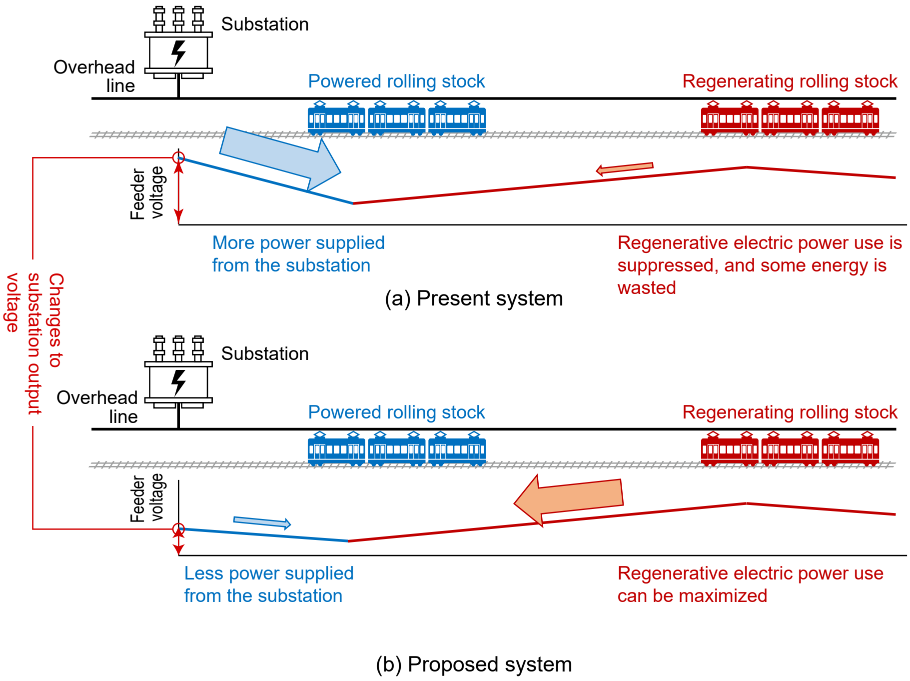


Fig. 5 Optimization of feeder voltage control

To achieve these operations, we devised the “Optimal Feeder Voltage Control Architecture” shown in Fig. 6.

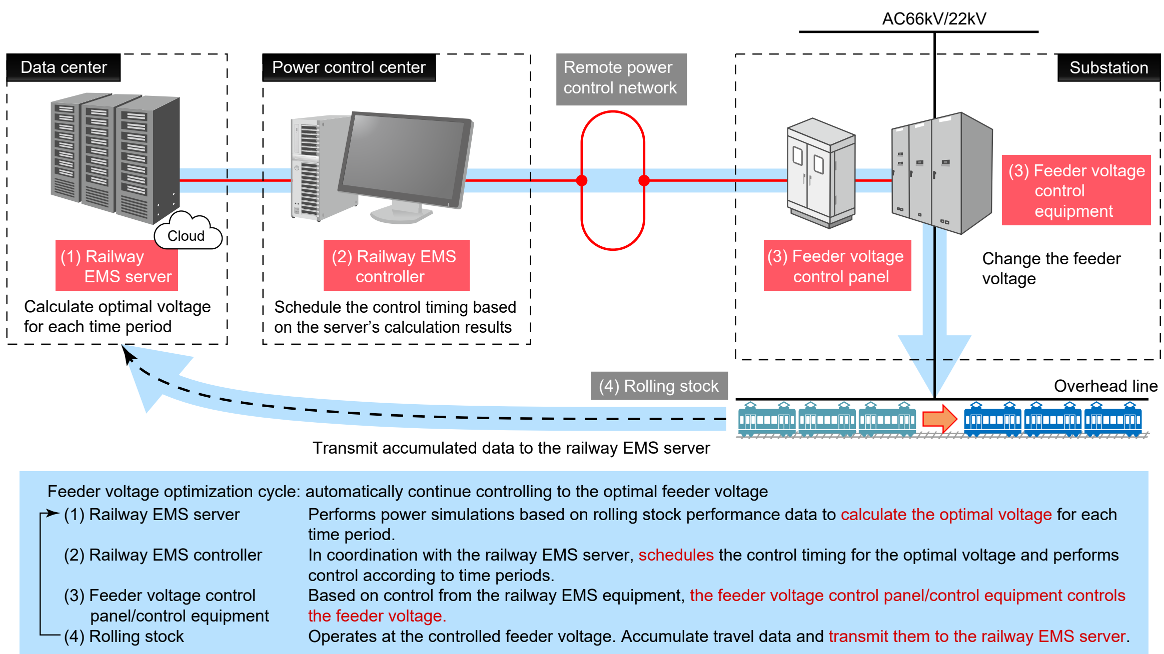


Fig. 6 Example of the optimal feeder voltage control architecture and optimization cycle

This architecture enables calculation and control of optimal feeder voltage for each time period, promoting effective use of surplus regenerative electric power. This achieves a balance between minimizing energy used for railway operations and reducing electricity charges, contributing to achieving carbon neutrality. We are currently building our proprietary feeder voltage optimization algorithm and are working to calculate the optimal voltage more efficiently.

3.3 Energy-efficient train operation control

In the past, we worked on energy-saving measures for individual trainsets, such as studying energy-saving run curves; however, we are currently also advancing efforts to develop energy-saving solutions based on overall optimization that takes into account operation control for multiple trainsets. For example, we are studying powering timing adjustment control to suppress the voltage drops in overhead lines, as well as arrival time adjustment control based on congestion level, which are shown in Fig. 7.

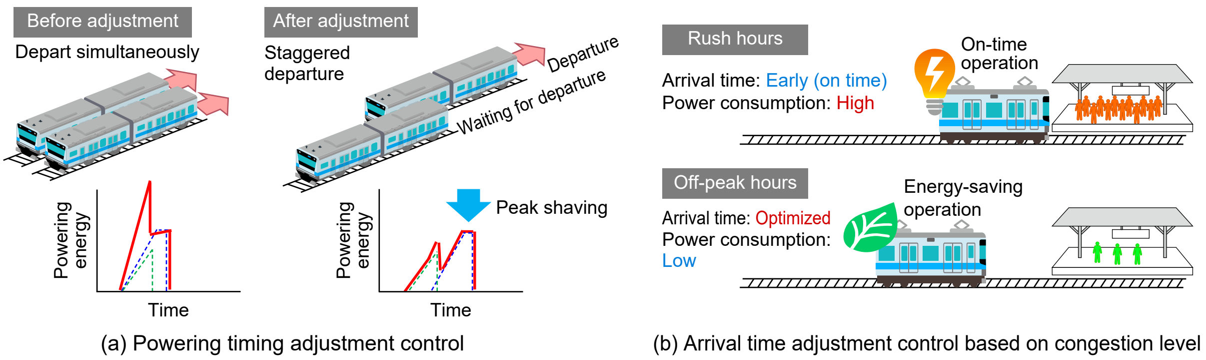


Fig. 7 Energy-efficient train operation control

For powering timing adjustment control, the timetable is adjusted to minimize or eliminate overlapping powering activities by multiple trainsets within each substation section. As a result, given that the current flowing through overhead lines can be leveled and peak current can be suppressed, transmission losses in overhead lines can be reduced. This also suppresses any decreases in the efficiency of onboard equipment and acceleration performance due to voltage drops, contributing to energy savings.

For arrival time adjustment control based on congestion level, whether to adopt energy-saving-priority operation or operation according to the timetable is determined within a range that does not impair passenger convenience. For example, in time periods and sections with fewer passengers, there is sufficient margin in boarding and alighting times at stations, so a run curve with even greater energy savings is adopted to reduce energy consumption.

In this way, we are advancing initiatives that add an energy-reduction perspective to train operations.

4. Energy Optimization for the Entire Railway Business

Combining all solutions described above – using data to select the most efficient solutions for each location – our vision is to achieve both overall power optimization for the entire railway (as shown in Fig. 8) and operation optimization which also leads to improved passenger convenience.

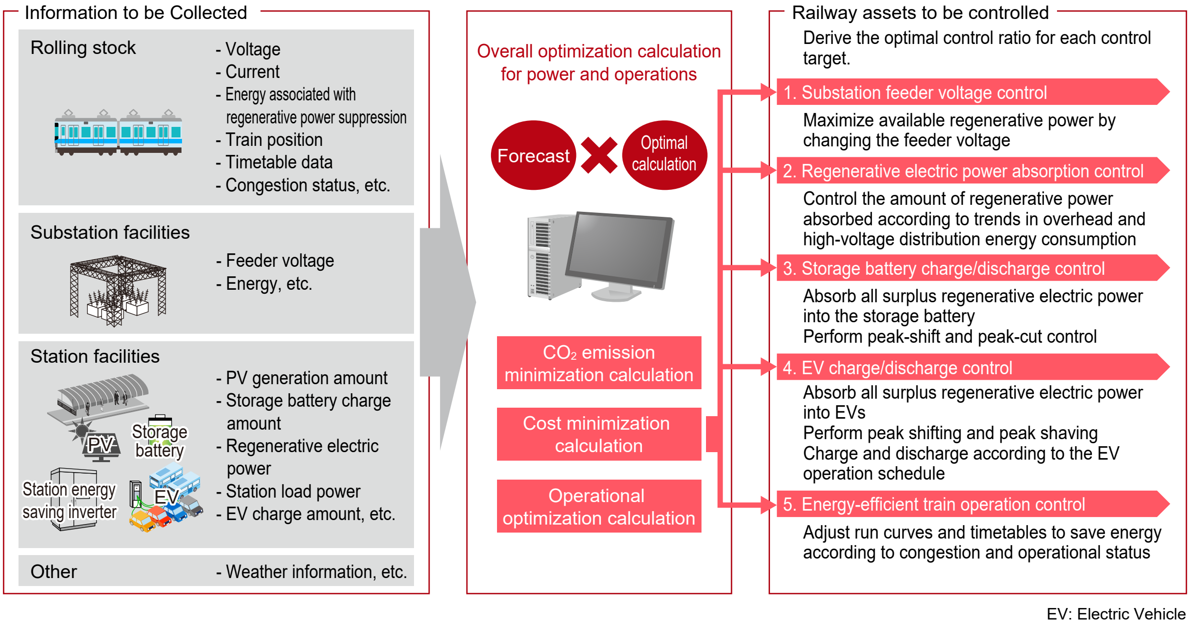


Fig. 8 Energy optimization for the entire railway business

From a medium-term perspective of several years, operation plans and the associated power demand change due to factors such as the introduction of new rolling stock and changes in passenger flow due to urban development. From a short-term perspective of about one year, operation plans and power demand also fluctuate due to timetable revisions, weather conditions, and various special events. To respond to these changes while maintaining passenger convenience, simulations are conducted to optimize power use by utilizing data on rolling stock, substations, stations, weather, and other factors.

In this way, we are aiming to establish simulation technology that achieves overall optimization by combining individual energy-saving solutions.

5. Future Outlook

In the future, as shown in Fig. 9, we aim to achieve further energy optimization through rail-based initiatives in collaboration with communities along the railway network. For example, the development of station-centered microgrids in communities along railway lines will enable energy optimization beyond the railway sector. In addition, leveraging railway assets during emergencies such as large-scale disasters enables the supply of emergency power to communities along railway lines, strengthening power resilience and increasing the value of the railway corridor. Furthermore, given the high level of power consumption in the railway business domain, suppressing railway power demand as needed and using railway assets as adjustment resources makes it possible to respond to power shortages in the electricity market. Through these initiatives, we aim for energy optimization beyond the railway business domain.

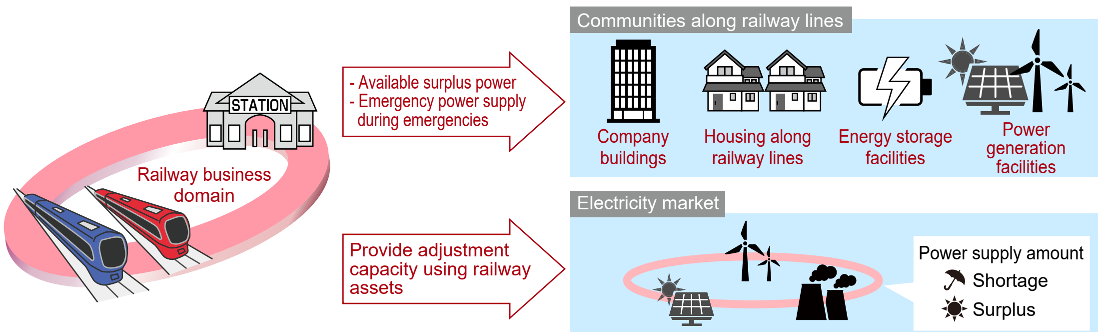


Fig. 9 Collaboration with non-railway business domains

6. Conclusion

Preventing global warming is an important issue in achieving a sustainable society, and efforts to achieve carbon neutrality are underway worldwide. This paper outlined our specific solutions for decarbonization, starting with data analysis using the digital platform Serendie.

Going forward, we will contribute to further accelerating the achievement of carbon neutrality by applying insights gained through various solutions to new solutions and by working to develop solutions in collaboration with various business domains beyond the railway domain.

Reference

(1) Ubukata, N., et al.: Initiatives Toward Energy-saving Optimal Rolling Stock Systems, Railway Cybernetics Symposium Papers, No. 48, 503 (2012)

"MHPB" Module: Driving Innovation in Future of Battery Solutions

Author: *Tatsuya Morioka**

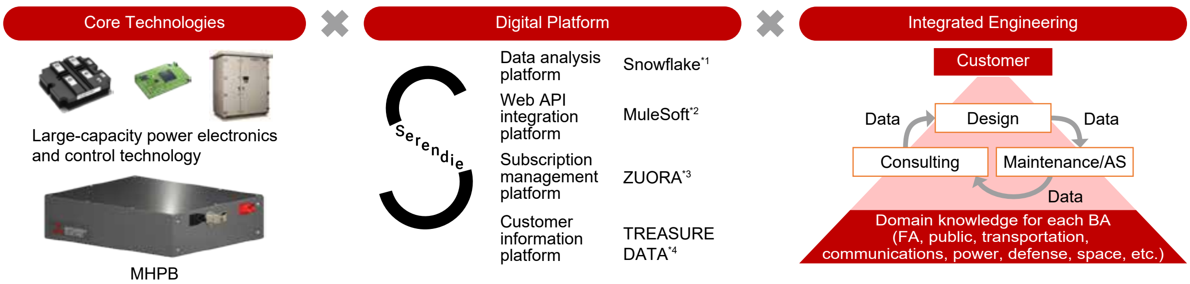
**Itami Works*

Abstract

To achieve a decarbonized society, advances in energy storage technology are becoming important for promoting the use of renewable energy and electrification. Batteries, which are key to electrification, have different characteristics such as output, capacity and service life depending on the product, and are used selectively according to the application. New battery-related technologies such as fast charging and wireless charging are also advancing, which is expanding their potential. An example of this is in the railway industry, where battery installation on railway vehicles is progressing for non-electrified sections and emergency operations, however issues remain such as the need for many batteries to secure output and capacity, and the need for a considerable charging time. Mitsubishi Electric Corporation has newly developed the next-generation battery module Mitsubishi High Power Battery (MHPB) which excels in high power density, long service life and increased capacity, and will contribute to promoting decarbonization through energy solutions.

1. Introduction

This paper outlines advances in our energy storage technology and the development of energy solutions as a means of addressing social issues, and presents the potential of the newly developed next-generation battery module. Our company provides battery and energy solutions that help resolve the energy challenges of our customers and potential needs/seeds by integrating battery-centered core technologies and integrated engineering that supports the entire lifecycle through our proprietary digital platform "Serendie" (Fig. 1).



API: Application Programming Interface, AS: After Service, BA: Business Area
*1 Snowflake is a registered trademark of the Snowflake Inc. *2 MuleSoft is a registered trademark of the Salesforce, Inc.
*3 ZUORA is a registered trademark of Zuora, Inc. *4 TREASURE DATA is a registered trademark of Treasure Data, Inc.

Fig. 1 Battery and energy solutions provided by our company

2. Battery and Energy Solutions

As shown in Fig. 1, we are providing battery and energy solutions by integrating battery-centered core technologies and integrated engineering that supports the entire lifecycle through our proprietary digital platform Serendie.

This chapter outlines the core technologies, digital platform, and integrated engineering that comprises this solution.

2.1 Core technologies

Figure 2 outlines our core technologies. High-efficiency power electronics technology cultivated in the railway business reduces power consumption and enables efficient use of energy. By combining energy management solutions (EMS), cybersecurity technologies, and state of charge (SoC)/state of health (SoH) estimation technologies developed by our company, we are establishing core technologies that boost the value of solutions. As an external collaboration technology, in May 2024 we also concluded a business alliance with Musashi Energy Solutions Co., Ltd. regarding the next-generation battery module and battery management system (BMS). Musashi Energy Solutions Co., Ltd. covers the design, development, and manufacturing of next-generation battery cells, and our company is responsible for the design, development, and manufacturing of the next-generation battery module and BMS. The next-generation battery module is outlined in Chapter 3.

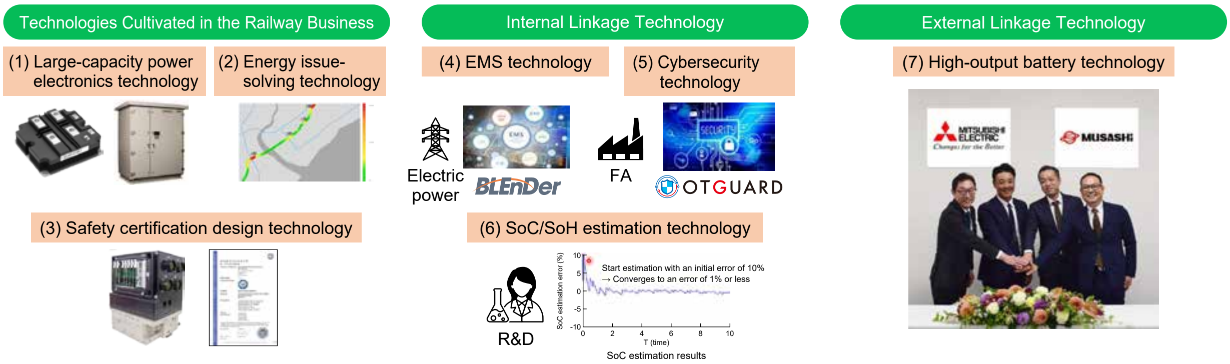


Fig. 2 Our core technologies

2.2 Digital platform

We built our proprietary digital platform Serendie to create new value from data. Serendie is a platform that allows diverse human resources to demonstrate technical capabilities and creativity and provide new services and solutions.

In railway energy solutions, the digital platform Serendie collects operational data on the charge/discharge status of onboard MHPB, and through large-scale data analysis, proposes optimal charge/discharge patterns and battery installation capacities appropriate to each railway line. Determining when to replace expensive batteries is also important for railway operators. By analyzing operational data from onboard batteries, SoH can be estimated with a high level of accuracy, enabling more precise evaluation of battery degradation.

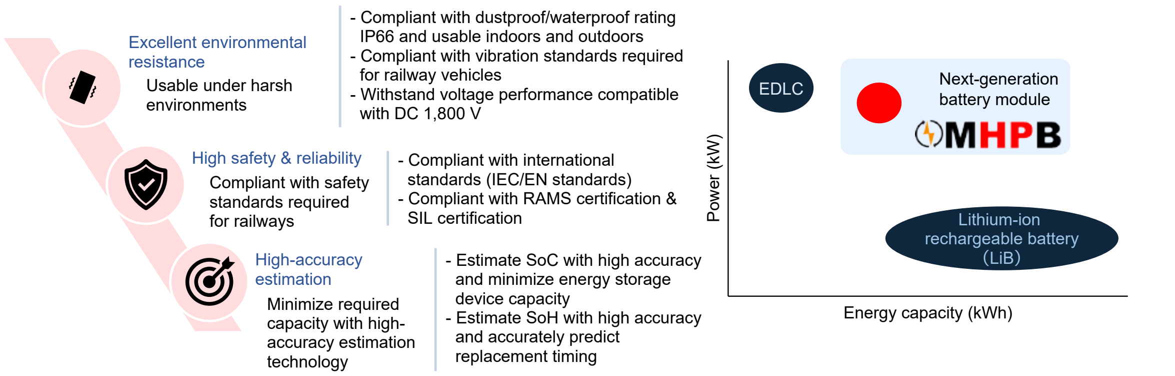
2.3 Integrated engineering

Based on our technologies in each field, we are providing total support for product/system implementation, operation, maintenance, after-sales service, and system upgrades, and by leveraging data from each lifecycle phase, we are achieving integrated engineering that contributes to sustained customer value enhancement. Optimal design of the overall system is required from the perspective of integrated engineering. An example is when applying the MHPB module to railway vehicles—energy optimization of the entire railway system is achieved by linking the operation management system and implementing operation management in accordance with the battery status.

3. Features of the Next-generation Battery Module MHPB

Figure 3 outlines the features of the next-generation battery module MHPB. Given that MHPB is installed in railway vehicles, it is designed to ensure safety, durability and reliability, taking into consideration severe operating environments such as vibrations and outdoor temperature changes, in addition to meeting the required standards.

MHPB also offers three characteristics: high power density, long service life, and operability at high temperatures. In terms of high power density, compared with general lithium-ion rechargeable batteries, MHPB has up to about six times the power density as shown on the right side of Fig. 3, and because high-power rapid charge/discharge is possible, contributes to smaller and lighter battery systems. And given that the maximum service life is as long as 16 years, the number of battery replacements can be reduced, enabling a lower life cycle cost (LCC). Furthermore, MHPB can operate in high- and low-temperature environments, enabling stable operation in the range from −40°C to 70°C.



IP: Ingress Protection, IEC: International Electrotechnical Commission, EN: European Norm,
RAMS certification: Reliability, Availability, Maintainability, Safety; certification of safety and reliability of the entire system,
SIL certification: Safety Integrity Level; certification related to functional safety, EDLC: electric double-layer capacitor

Fig. 3 Characteristics of the next-generation battery module MHPB

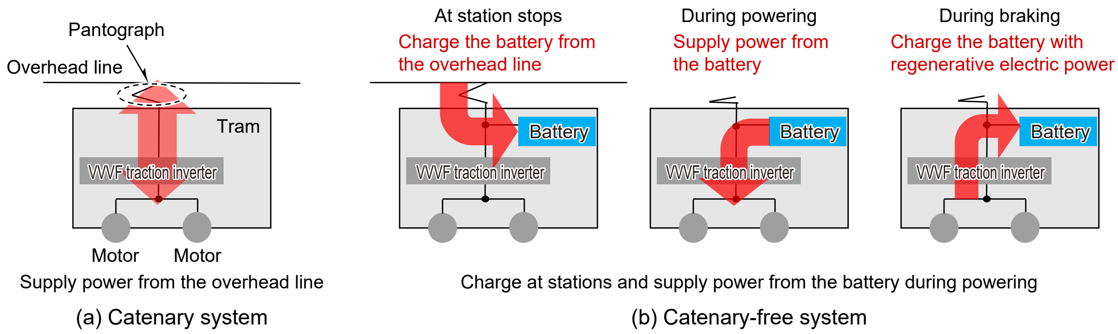
With these features, it excels at absorbing/outputting high power for about 30 seconds to 1 minute, making it an optimal module for applications such as slimming equipment through power peak cutting and energy savings by absorbing regenerative electric power.

4. Application Examples of the Next-generation Battery Module MHPB

Leveraging the characteristics of the next-generation battery module MHPB outlined in Chapter 3, here are details of three application cases: application to catenary-free trams, use for power peak cutting, and eliminating power wiring for warehouse stacker cranes.

4.1 Battery introduction for railway vehicles: catenary-free trams

Mounting batteries on railway vehicles and supplying power from the battery during powering and charging the battery with regenerative electric power during braking helps to achieve catenary-free operation that eliminates overhead lines supplying power. Figure 4 shows an overview of the catenary-free system. Catenary-free systems offer benefits such as eliminating overhead lines, providing a pleasing urban landscape, and reducing maintenance work.



VVVF: Variable Voltage Variable Frequency

Fig. 4 Catenary-free system

Catenary-free trams are an application where MHPB's three characteristics—high power density, long service life, and operability at high temperatures—can be leveraged. Figure 5 shows our solution for battery introduction in catenary-free trams. Note that this solution is available not only for catenary-free trams but also to hybrid systems that combine hydrogen fuel cells, etc. with MHPB modules.

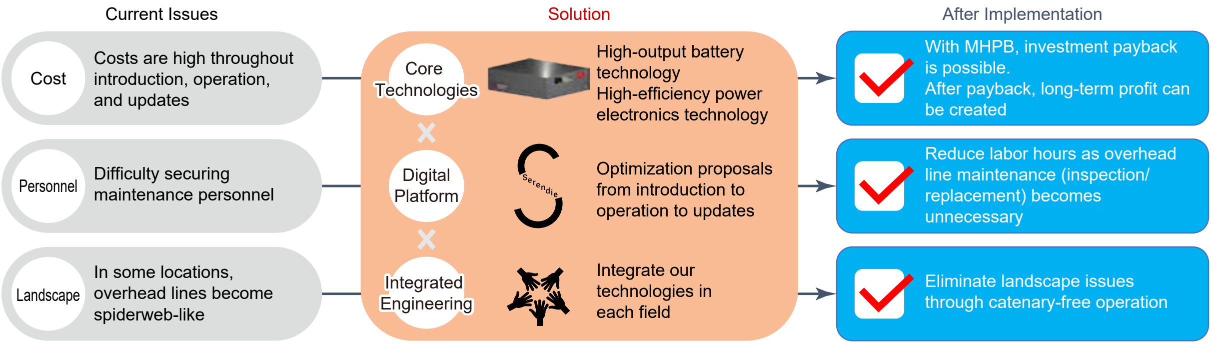


Fig. 5 Our solution for introducing batteries in catenary-free trams

4.2 Introducing batteries for power peak cutting applications

A peak-cut control method has been developed available where a battery is applied to a conventional power system. In general, during high load, the battery is discharged and power is supplied to the load from both the conventional power source and the battery, thereby reducing the peak load on the power source. This control has various applications such as reducing factory power capacity, and railway applications are outlined here. Figure 6 shows the railway peak-cut system.

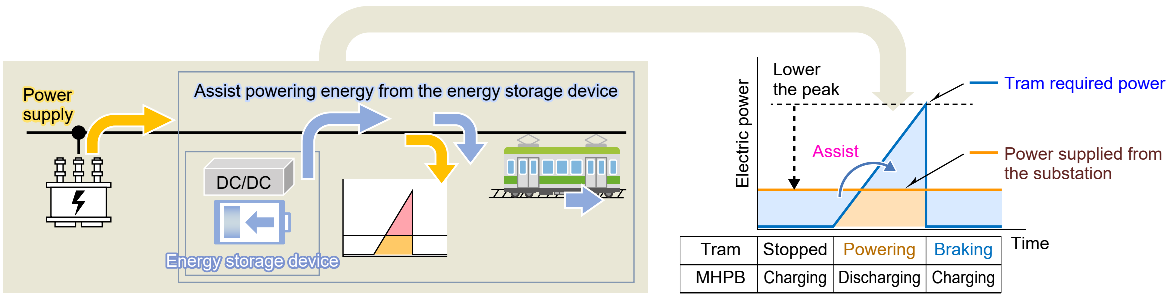


Fig. 6 Railway peak-cut system

In peak cutting, the onboard battery is first charged from the overhead line while stopped. After that, when the power required by the train increases during powering, discharging from the battery to assist makes it possible to reduce the maximum power supplied from the substation. During braking, regenerative electric power is also used to charge the battery in preparation for subsequent powering. Figure 7 shows our solution for battery introduction for peak cutting applications.

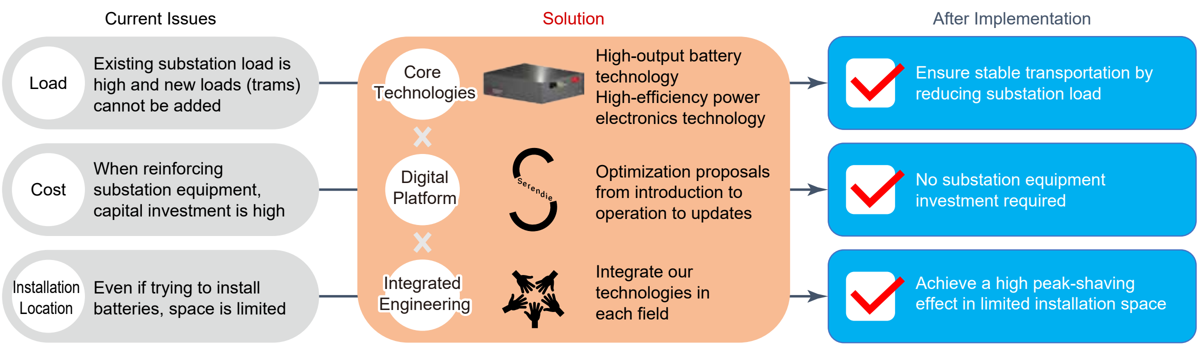


Fig. 7 Our solution for battery introduction for peak cutting applications

4.3 Battery introduction for stacker cranes

This section outlines application examples other than railway use. Stacker cranes operate while moving up/down and left/right to load and unload items in logistics warehouses and similar facilities. Currently, many systems use trolley lines, but by newly introducing batteries, removal of trolley lines becomes possible. By recovering the kinetic energy into the battery while descending, improved energy efficiency can be expected. Figure 8 shows an overview of the battery system for stacker cranes, and Fig. 9 shows our solution.

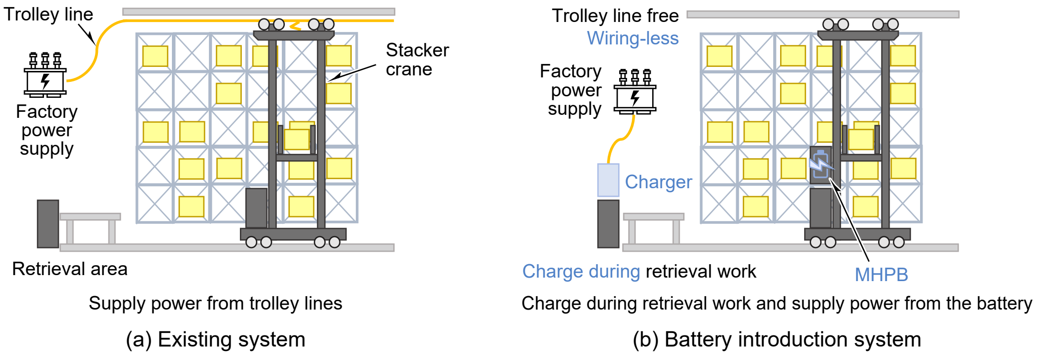


Fig. 8 Battery system for stacker cranes

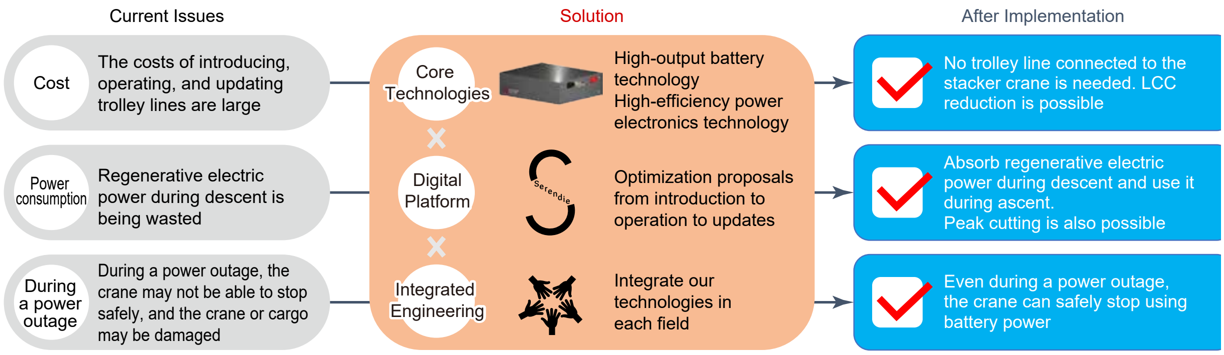


Fig. 9 Our solution for battery introduction for stacker crane applications

5. Conclusion

We outlined the development of battery and energy solutions using the newly developed MHPB by our company, to address social issues such as decarbonization and energy problems. As a result, the spread and expanded use of electric mobility will accelerate even in the transportation sector, and results such as effective energy utilization and CO_2 reduction can be expected.

With relentless technological innovation and limitless creativity, we will continue to promote initiatives toward solving social issues and aim to achieve a sustainable energy society.

Railway Air Conditioning Systems for European Market Using Natural Refrigerant R290 (Propane)

Authors: *Takeshi Inoue*, Wahei Shingu**

**Itami Works*

Abstract

With the tightening of refrigerant regulations toward achieving a sustainable society, the railway air conditioning industry is seeking natural refrigerants with Low Global Warming Potential (GWP) and low environmental impact. R290 (C3H8 (propane)) has drawn attention as a refrigerant offering excellent cooling performance and low environmental impact, but given that it is highly flammable, risk assessment and fire prevention measures are essential for its adoption. Accordingly, Mitsubishi Electric Corporation developed a safe and highly reliable railway air conditioning system compliant with European regulations, and designed and verified a refrigeration cycle using R290. We achieved both environmental performance and safety and established practical applicability as a railway air conditioning system by using a reduced-refrigerant design, running multiple small independent refrigeration cycles, placing brazed joints in optimal locations, and adopting a rapid discharge mechanism for leaked refrigerant. This achievement has been adopted for a commuter train air conditioning system in Munich, Germany, and will contribute to expanding the application of R290 throughout the railway air conditioning industry.

1. Introduction

Mitsubishi Electric Klimat Transportation Systems S.p.A., an Italian subsidiary, received an order for a railway air conditioning system using R290 natural refrigerant for commuter trains in Munich, Germany. This is the first time a Japanese company received an order for an air conditioning system using R290 for railway rolling stock[*1]. With refrigerants being reviewed from the perspective of reducing greenhouse gases in recent years, the introduction of environmentally considerate refrigerants is being sought. This development explores adopting R290 refrigerant, which has low environmental impact, in the railway air conditioning industry—yet, given that R290 has a high level of flammability, measures are required to reduce refrigerant leakage and fire risks. This paper outlines the design of the refrigeration cycle used to develop a safe and highly reliable R290-based air conditioning system compliant with European regulations, as well as its safety measures.

2. Shifting from Conventional Refrigerants to Natural Refrigerants, and Regulatory Changes

The Sustainable Development Goals (SDGs) are guidelines adopted by UN member states in 2015, with the aim of to solving issues such as poverty, inequality, and environmental degradation by 2030. With 17 goals and 169 targets, they seek to achieve a society that leaves no one behind while maintaining a balance between the economy, society, and the environment. Companies play an important role in achieving these SDGs, and they must review their business strategies to help prevent global warming and address environmental pollution. The promotion of decarbonization and fluorocarbon refrigerant regulations in particular are driving the need to reduce CO_2 emissions and lower environmental impact.

European fluorinated gas regulations (commonly known as the "F-gas Regulation")[(1)] were promulgated in 2006 and came into effect in 2015, with the aim of reducing emissions of HFCs (hydrofluorocarbons), PFCs (perfluorocarbons), and SF_6 (sulfur hexafluoride). In addition to regulations on products and equipment, sales volumes are being reduced in stages through an HFC quota system.

*1 As of September 19, 2024, based on Mitsubishi Electric Corporation research

The Kigali Amendment (MOP28) to the Montreal Protocol is a framework for the phased reduction of the production and use of fluorocarbon refrigerants as part of measures to ensure protection of the ozone layer and combat global warming. As a result, refrigerant and air-conditioning equipment manufacturers are being forced to shift to Low GWP refrigerants. Per- and Polyfluoroalkyl Substances (PFAS), which are organofluorine compounds, also remain in the environment for long periods of time and are of concern for their impacts on living organisms—in Europe, their use is restricted by regulations governing PFAS. With the new regulatory proposal in 2023, some fluorocarbon refrigerants are also included, and after the transition period ends they will be prohibited, so future developments will need to be closely monitored.

R22 refrigerant had been mainstream in the past in Japan's air-conditioning industry, however, following amendments to the Montreal Protocol, production was phased down by 2020, and the shift to R407C and R410A progressed. R410A is used for residential and commercial air conditioning, while R407C is used domestically and R134a is used overseas for railway air conditioning systems.

With recent regulatory tightening, residential and commercial air conditioning is shifting to R32, which has a relatively low GWP, and conversion to even lower-GWP refrigerants is also being considered. In the European railway industry, demand is also increasing for HVAC (Heating, Ventilation, and Air Conditioning) systems using the natural refrigerant R290, from the perspective of reducing environmental impact. A comparison of refrigerants is shown in Table 1.

Table 1 Refrigerant comparison

	R22	R134a	R407C	R410A	R32	R290
Application	Old air conditioners	Car air conditioners	Air conditioners (R22 replacement)	Air conditioners	Air conditioners	Air conditioners (Low-GWP compliance for the European market)
Ozone Depletion Potential (ODP)	0.055	0	0	0	0	0
GWP	1810 *2	1430 *2	1774 *2	2088 *2	675 *2	0.02 *3
PFAS regulations	Not applicable	Applicable	Applicable	Not applicable	Not applicable	Not applicable

*2 Evaluation criteria based on the IPCC Fourth Assessment Report(2)
*3 Evaluation criteria based on the IPCC Sixth Assessment Report(3)

3. Characteristics of R290 as a Refrigerant

While R290 is extremely highly flammable given that it is generally known as propane gas, as a refrigerant it has excellent thermodynamic properties compared with other refrigerants such as R407C and R32.

(1) High-efficiency, energy-saving refrigerant

R290 has the characteristics of high evaporating pressure (low pressure) and low condensing pressure (high pressure). Therefore, when operating the refrigeration cycle under the same conditions, using R290 results in a lower compression ratio and can reduce the work done by the compressor (power consumption). For this reason, it can be said to be a very advantageous refrigerant for achieving energy savings.

(2) Suitable for operation in high outdoor-temperature environments

R290 not only has relatively low condensing pressure (high pressure) but also has the characteristic of low discharge gas temperature. The lower the discharge gas temperature, the more thermal stress on internal compressor components is reduced, thereby reducing compressor load during operation in high outdoor-temperature environments.

As an example showing these characteristics, Table 2 summarizes differences in the states of each refrigerant when cooling operation is performed at an evaporating temperature of 10°C and a condensing temperature of 45°C, assuming constant compression efficiency and volumetric efficiency of the compressor. This table shows that R290 is an excellent refrigerant with the characteristics of a small compression ratio and low discharge temperature.

Table 2 Comparison of refrigerant states during cooling operation

	R290	R32	R407C
Evaporating pressure (low pressure)	0.64MPa	1.11MPa	0.65MPa
Condensing pressure (high pressure)	1.53MPa	2.80MPa	1.75MPa
Compression ratio (condensing pressure ÷ evaporating pressure)	2.39	2.52	2.69
Discharge temperature	53°C	77°C	62°C

Evaporating temperature 10°C, condensing temperature 45°C

4. Risk Management for Flammable Refrigerants

As outlined in Chapter 2, the air conditioning industry is required to respond to various refrigerant regulations aimed at reducing environmental impact, however, R32 and R290 are flammable refrigerants, and R290 in particular is classified as a highly flammable refrigerant. Ensuring safety against ignition is required to use these flammable refrigerants safely.

Refrigerant ignites when all these three conditions are met: (1) Rapid leakage, (2) Presence of an ignition source, and (3) Formation of a flammable range. Therefore, risk assessment for flammable refrigerants determines ignition probability by multiplying the probabilities of these three conditions, and determination is made in accordance with each device's safety criteria. This risk assessment should be evaluated across the entire product lifecycle from delivery to disposal (logistics, installation, use, maintenance, and disposal).

Ignition probability of refrigerant = (1) Rapid leakage × (2) Presence of an ignition source × (3) Formation of a flammable range

When using the highly flammable refrigerant R290, sufficient safety measures are required based on this risk assessment. Specifically, measures must be taken to reduce the probability of rapid refrigerant leakage occurring, reduce the probability of encountering ignition sources, and also prevent the formation of a flammable range by reducing refrigerant charge and discharging leaked refrigerant.

5. Features of the Railway Air Conditioning System for the European Market

Measures against the ignition risk of leaked refrigerant are essential when introducing R290 into railway air conditioning systems that have a high level of public importance. In particular in Europe, as part of safety measures, the upper limit of refrigerant charge in refrigeration systems is specified by the European standard EN (European Norm) 378-1[4]. This upper limit is determined based on the flammability of the refrigerant used (lower flammability limit (LFL)) and the installation environment of the HVAC system; if this limit is exceeded, additional safety measures based on a risk assessment according to the usage environment, as outlined in Chapter 4, are required.

A standard railway air conditioning system is a unit type in which the indoor unit and outdoor unit are integrated, as shown in Fig. 1, and is mounted on the roof of the vehicle. The refrigeration cycle has a fully hermetic structure in which all related components are joined with brazing.

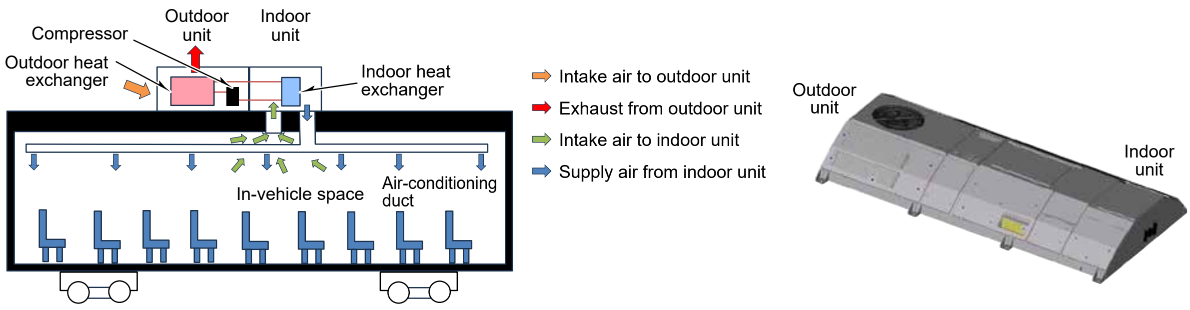


Fig. 1 Roof-mounted unit-type railway air conditioning system

The developed HVAC unit with R290 outlined in this paper is characterized by implementing the following three safety measures in this roof-mounted unit.

5.1 Multiple small refrigeration circuit design

Compliance with EN 378-1(4) is required to adopt R290 in railway air conditioning systems for the European market. The HVAC system outlined in this paper is mounted on the roof of a railway vehicle for the German market with an overall length of about 17m and a floor area of about 40m²; based on its installation environment, the maximum charge limit m_{max} of R290 is calculated using the formula shown in EN 378-1 as follows.

$$m_{max} = 2.5 \times LFL^{5/4} \times h_o \times A^{1/2}$$

- LFL (R290 lower flammability limit): 0.038kg/m³
- H_o (HVAC system installation height): 2.2m
- A (floor area of the installation space): 40m²

According to this calculation, the maximum charge limit for R290 is 583g.

The cooling capacity required per vehicle for this class of railway vehicles in Europe also is generally about 32kW; however, if a design similar to a refrigeration cycle using conventional R407C is applied, the amount of R290 required for one HVAC unit would be 5,000g, which is about nine times the maximum charge limit. Therefore, we improved the heat exchanger design and achieved a reduced-refrigerant design. Specifically, as shown in Table 3, by reducing the tube diameter of the heat exchanger and increasing its row pitch, the internal volume of the heat exchanger was reduced to about 1/4 of the conventional design. This design reduced the refrigerant amount and, while maintaining performance equivalent to the conventional unit, suppressed the required refrigerant amount per vehicle to 2,000g.

Table 3 Comparison of heat exchanger specifications

		R407C (conventional unit)	R290 (developed unit)
Reduced tube diameter (mm)		Outer diameter 6 (thickness 0.21)	Outer diameter 5 (thickness 0.36)
Increased tube row pitch (mm)		13.00	17.32
Increased tube stage pitch (mm)		15.00	20.00
Reduced fin pitch (mm)		3.50	2.00
Indoor heat exchanger volume (L)		80.5	62.1
	Inner tube internal volume (L)	10.1	2.6
Outdoor heat exchanger volume (L)		98.3	62.0
	Inner tube internal volume (L)	12.3	2.6

Furthermore, by dividing this refrigerant and charging 500g each into four independent small refrigeration circuits, it was kept within the EN 378-1 requirements and below the lower flammability limit. This eliminated the need for special safety measures and risk assessment against fire risk, ensuring a high level of safety for the HVAC system.

The design with four refrigeration cycles is also suitable for railway air conditioning systems not only for ensuring safety, but also in the following respects.

(1) Comfortable control of cabin temperature

ON/OFF control of each refrigeration cycle means cooling capacity can be adjusted in five steps—0%, 25%, 50%, 75%, and 100%—making it possible to maintain the cabin temperature to an appropriate level.

(2) High redundancy and reliability

Four independent refrigeration cycles ensure high redundancy and also contribute to stable train operation. As global warming progresses, outdoor temperatures are rising, and the importance of HVAC systems is increasing further to improve in-vehicle comfort. For railway vehicles with a high level of public importance, high redundancy of HVAC systems is a key factor directly linked to sound train operation.

The developed unit is designed to meet these requirements and is an HVAC system that balances safety, comfort, and reliability.

5.2 Eliminating brazed refrigerant piping in the in-vehicle area

If refrigerant leaks within the in-vehicle area of the HVAC system, because that area and the passenger compartment are connected via the return opening and supply opening, there is a possibility that leaked refrigerant may flow into the passenger compartment. The refrigerant charge will be kept below the limit specified by safety standards; however, the risk of refrigerant leakage into the passenger compartment should be reduced as much as possible.

Therefore, to further improve safety, the internal layout design of the HVAC system was improved as shown in Fig. 2. Conventionally, the connection area between the hairpin tubes of the in-vehicle heat exchanger and piping, which was included in the in-vehicle area, was newly established as a "second outdoor area," and seamless piping with no brazed joints was adopted for piping that penetrates the in-vehicle area sandwiched between the first outdoor area and the second outdoor area.

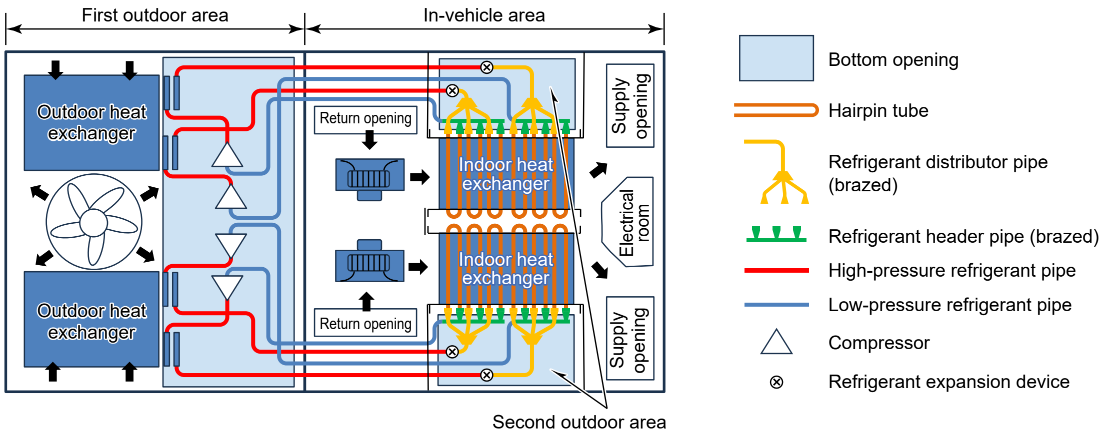


Fig. 2 Layout diagram of refrigeration cycle components

This design change completely eliminated brazed joints, which carry a high risk of refrigerant leakage, from the in-vehicle area, making it possible to keep the risk of refrigerant leakage into the passenger compartment extremely low.

5.3 Measures to discharge leaked refrigerant from the brazed section

Although the brazed section was positioned placed outside the in-vehicle area, measures are necessary so that refrigerant will not remain within the area even if it leaks there. Therefore, in the developed unit, an opening was provided in the bottom surface of the area where brazed components are located. The light-blue area shown in Fig. 2 (bottom opening) corresponds to this opening.

Because R290 has a higher specific gravity than air, even if it leaks in the brazed section, it moves to the bottom of the unit and is released to the outside through the opening. railway air conditioning systems are installed on the roof and the surroundings are an open space; leaked refrigerant disperses and its concentration will not rise into the flammable range, thereby ensuring safety.

6. Conclusion

From the perspective of preventing global warming, we examined fire countermeasures for applying R290 to railway air conditioning systems and proposed a design method for a safe and highly reliable refrigeration system. In particular, designs that combined practicality and safety—such as limiting the refrigerant charge based on EN 378-1(4), multiple small refrigeration circuit design, eliminating brazed joints in the in-vehicle area, and a rapid discharge mechanism in the event of refrigerant leakage—were effective. This enabled us to take an important step toward expanding the application of R290 in the railway air conditioning industry. Going forward, we will continue research aimed at further improving safety and efficiency based on broader field testing and operational data.

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