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Energy System
to Achieve Decarbonization
Energy Systems for Achieving Carbon Neutrality

FEATURED ARTICLES

Power Grids for a Sustainable Energy Future
Energy Solutions for GX
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Creativity Consists in the Mental Ability to Sense and Respond to the World around Us

Possibilities Opened up by Putting "Natural-born Intelligence" to Work

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Climate change and other difficult challenges facing global society are prompting a search for new ways of approaching social innovation. At a time when increasingly complex circumstances are rendering accepted wisdom and existing systems of knowledge less relevant, the concept of "natural-born intelligence" put forward by the theoretical biologist Professor Yukio-Pegio Gunji represents a potential key to overcoming a growing rigidity in societal systems and technology. How can this natural-born intelligence be put to work in a society that is in thrall to artificial intelligence? A proponent of the idea that the natural-born intelligence of human beings is the wellspring of innovation, Professor Gunji here discusses this proposition with his former student, Youichi Horry, who has been involved in a wide variety of work at Hitachi, Ltd.

Finding Ways to Compare Social and Environmental Value

——I understand you have known one another for a long time?

Horry: Since 1987, it has been 36 years now. Professor Gunji came from the graduate school to teach at the Department of Earth and Planetary Sciences in the Faculty of Science where I was studying at Kobe University. While I may not be his greatest acolyte as such, I was his first. I learned all manner of things from him, whether it be how to look at things, fundamental ways of thinking, or what stance to take as a researcher.

Gunji: He still often drops in at the laboratory and offers his advice to the students. I expect it is encouraging for them to see a former student who is playing an active role in society and I am always pleased to see him. However, I have not heard much about what he has been up to recently (laughing).

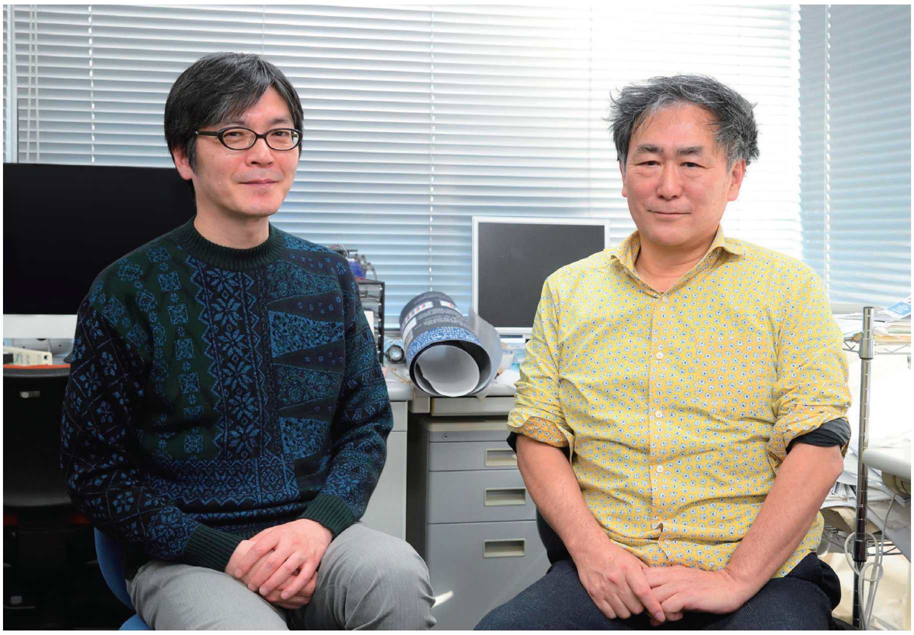
——In that case, Horry-san, could you start by telling us about your recent activities?

Horry: I am currently working on the development of platform technologies to support the transition to a sustainable society. One of the main things I am involved with is the social and environmental return on invested capital (hereinafter environmental ROIC) approach to quantifying total value of economic activity. Along with decarbonization, which can be thought of as a challenge for the entire world, there has been strong demand recently, especially in Europe, for making the shift to a sustainable society in ways that also take account of the circular economy, biodiversity, and human rights issues. Such measures are closely interlinked with societal systems and corporate management strategy, with people looking at making it obligatory for companies to disclose non-financial information. This has included work that went into establishing the Task Force on Climate-related Financial Disclosures (TCFD) and Taskforce on Nature-related Financial Disclosures (TNFD) as well as the Task Force on Social-related Financial Disclosures (TSFD) that also focuses on respect for human rights.

While this is to some extent a rule-making competition, creating a genuinely sustainable society will require that these issues be addressed in a comprehensive manner, instead of addressing each issue individually. We developed environmental ROIC as a decision-making support tool that will facilitate comprehensive and realistic action, one that works by quantifying the social and environmental value produced by corporate projects and other economic activity, thereby providing an insight into the benefits and outcomes of this work that takes account of society and the environment (see figure on next page).

Environmental ROIC looks at how various elements interrelate, considering the different products, technologies, and other individual components of economic activity and determining which globally recognized indicators they contribute to, such as the Sustainable Development Goals (SDGs). The total social and environmental value (V) of the economic activity is then calculated using the formula shown in the figure.

In an example application of the technique to the electrical facilities at a water treatment plant, we used carbon dioxide (CO_2) emissions reduction as a yardstick for technology for reducing the power required to operate the plant. This involved calculating a contribution factor (Y_k) by multiplying



annual power consumption by the CO_2 emission coefficient for the location, where annual power consumption (kWh) is the product of multiplying the power required to operate the plant (kW) by the annual operating hours (h). The social and environmental value V is given by summing the Y_k values, weighted by the C_k coefficients, after first converting them to financial values. The environmental ROIC is then obtained by adding this calculated value of V to the financial return on the project and dividing by the amount of capital invested.

Need for Standardization of Coefficients to Enable Value Comparison

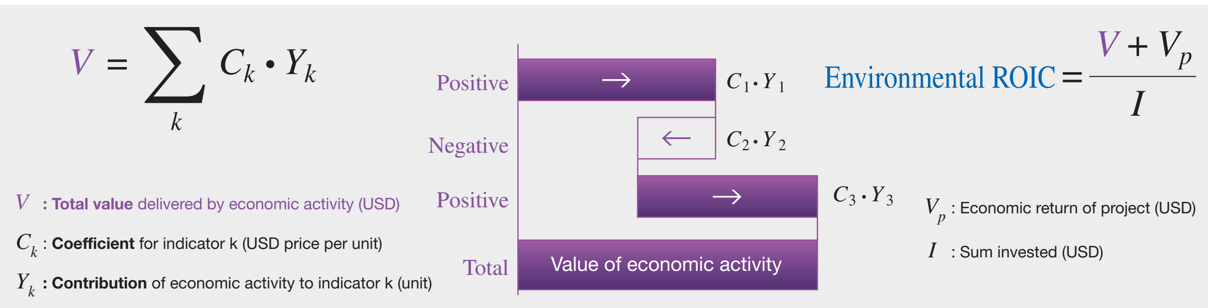
——How do you go about determining the coefficients?

Horry: What matters most is to standardize how the C_k coefficients are determined. To explain the role that coefficients play, consider how Hitachi has operated an internal carbon pricing system since 2019. This system attaches a price of 14,000 yen/ton to reductions in CO_2 emissions by newly installed equipment, the intention being to highlight the extent to which such capital investments reduce emissions. In this example, this price serves as a coefficient. That is, it is a numerical expression of what Hitachi values.

As for how coefficients are determined, one way is for the person making the decision to set the value by themselves. Alternative objective approaches are to determine a market price based on market principles or to use cost-benefit (B/C) analysis, or to calculate a value using data and an algorithm.

However, whichever method you choose, the decision will reflect your values and thinking. Moreover, economic activity will have participants on many different levels, such as companies or workplaces and local or national government, with each of these organizations having different values. That is, different organizations place weight on different elements and this will cause a lot of variability in the coefficient lists.

If meaningful comparisons are to be made between quantified values, it is essential to standardize the list of coefficients. To achieve this, we started by publishing the lists so that the participants could see what others had chosen. We hoped that this would encourage convergence as people were prompted to look at what others had come up with and make changes where their own coefficients were out of step.



Figure—Environmental ROIC Technique for Quantifying Social and Environment Value of an Economic Activity

Collating coefficients as lists is necessary for them to be incorporated into programs automatically and also to enable appropriate adjustments to be made to the decision-making by artificial intelligence. Having anticipated this, we are currently making environmental ROIC calculations for customers in a wide range of different industries.

Revising the Formulation of "Problem" and "Solution"

Gunji: I see. That is very interesting. Speaking in fundamental terms, the typical way we think about issues, whether they relate to the environment or something else, is in terms of there being a "problem" and a "solution." However, doubt arises as to whether the problem really is a problem. A problem is something that only becomes clear when we frame it in some way. While we don't necessarily need to look beyond this framing to bring together the relevant factors, it is also possible, conversely, for us to choose a framework that suits our own purposes, pushing aside those aspects we prefer to ignore. This means that our ability to resolve a problem depends in many cases on whether we can choose a framework that is convenient to ourselves. As it is easy to get stuck on this way of looking at things, it may be that we also need to consider stepping away from our chosen framing.

Horry: That is right. Environmental ROIC itself is not intended as a way of defining problems. Rather, we anticipated that problems might arise from the variability of coefficient lists.

Gunji: Whether it be environmental problems or anything else, the way it often works is that someone has something they want to accomplish and science is used to achieve it. While people often talk about the importance of objectivity in science, the issue is whether objectivity and the like are present to begin with. This is because a strict insistence on objectivity risks excluding the human perspective to the extent that humans could be allowed to become extinct. In that regard, having a variety of different coefficient lists represents a form of dynamism in the sense of a jumble of different subjective perspectives. By taking advantage of this, it may be possible to deliver a more successful outcome than could be achieved by something that has been carefully designed from scratch.

Horry: Environmental ROIC works by combining elements of various different types. As the number of such elements was not stipulated from the outset, they can be added indefinitely. While this has the potential to become somewhat arbitrary, I believe it also aligns in some respects with Gunji-sensei's own thinking.

Youichi Horry, Ph.D.

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After graduating with a degree in earth sciences from the Graduate School of Science at Kobe University, he joined Hitachi, Ltd. in 1990 at the Central Research Laboratory where he worked on research into computer music and graphics. In 1997, he took up a position as a Visiting Researcher at the Institut National Recherche en Informatique et en Automatique (INRIA) in France, began his research into human interaction in 2000, and established the Hitachi Human Interaction Laboratory (HHIL) in 2003. Since 2010, he has been working on management science for social infrastructure at a number of institutions, including Hitachi's Advanced Research Laboratory, Central Research Laboratory, and the Matsudo Research Laboratory of Hitachi Plant Technologies, Ltd. He was appointed to his current position in 2022.

He obtained a Ph.D. in engineering from Waseda University in 2018. He was appointed a C4IRJ fellow of the World Economic Forum in 2020 and an expert at WG5 of ISO TC323 (Circular Economy) in 2022.

Seeking Optimal Outcomes that Allow for External Factors

Gunji: The concept of self-organized criticality was proposed and modeled by Per Bak, a Danish theoretical physicist. The idea is that, when the behavior of certain phenomena or materials is modeled mathematically without stipulating a framing or problem in advance, they achieve a dynamic stability on their own that is in effect a close approximation to the optimal, even in a disordered open system that is exposed to external factors. This is in complete opposition to the conventional approach to design that seeks to obtain optimal solutions under ordered conditions.

One example of self-organized criticality is the sand pile model. When grains of sand are progressively dropped from above onto a flat surface, a pile tends to accumulate up to the point where a section of the pile collapses, a process that repeats over and over again as more sand is dropped. While it is the slope of the pile that determines when such collapses will happen, this in turn depends on the physical properties of the sand (size and friction). When this sand pile model experiment is run, the collapses happen on a range of different scales such that the frequency with which a collapse of any given size occurs decreases as collapse size increases. That is, the relationship between collapse size and frequency follows a power law[*1].

When phenomena follow a power law, it is impossible to predict the scale of future events based on the mean size of past events. That is, a very small change in conditions can result in a phase transition. This is why they are called critical phenomena and they occur frequently in nature, earthquakes being one example.

While Per Bak passed away in 2002, ideas of this nature are once again attracting a lot of attention. In the case of animal gait, for example, a probability distribution for step length that follows a power law is called a "Lévy walk." Animals are known to use this to search for food efficiently. Formulated as a mathematical model, this could be used to improve efficiency when searching for something under unknown conditions. While a variety of models, our own included, have been proposed to show the mechanisms that are incorporated into the way animals walk so that they exhibit criticality, my own view is that it represents a form of natural-born intelligence.

While I will talk more about natural-born intelligence later on, in simple terms I describe it as intelligence that arises from sensing and responding to external factors. My goal is to develop a theory of this natural-born intelligence and incorporate it into an intelligence model that provides ways of responding not only to predetermined conditions, but also to unanticipated external factors.

In the case of your own environmental ROIC, you do not impose a predetermined framework on the indicators and coefficient lists. By avoiding this, it may be that environmental ROIC will evolve dynamically by incorporating not only those factors that can be anticipated in advance, but also mechanisms for dealing with the unexpected or factors that conflict with one another.

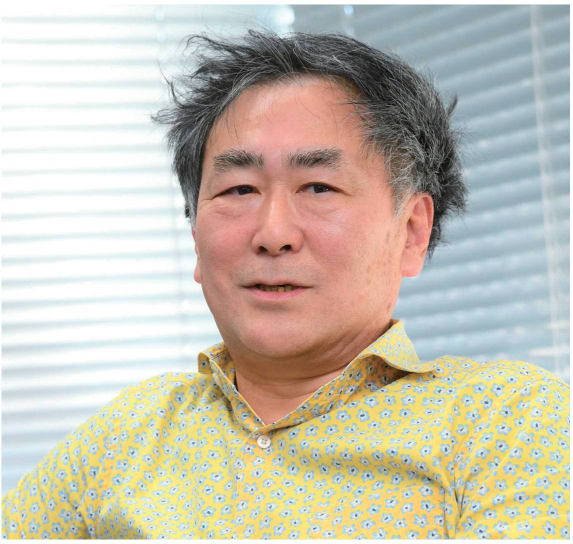
Horry: That's right. A list that allows for the comparison of coefficient values does not yet exist. Once it does, it would become possible, for example, to make explicit numeric comparisons of the different weightings that emerging nations and developed nations place on human rights, something that currently has only an implicit expression in policies. In a certain respect, this is a case of contradictory factors coming into conflict with one another and can be expected to drive convergence.

*1 Power law
A type of statistical model in which the values for a small subset of the population are much larger than the rest. The mean has no meaning for data that follows a power law.

While people tend to think of coefficients as being objective, I talked earlier about how the choice of whether to determine them objectively is in fact a subjective one, meaning that they embody people's values and opinions. On the other hand, decision-making calls for objective theory and data. Which is to say that the realm of coefficients is one where the objective and subjective are nested within one another, making it difficult in some regards to predict whether our lists will ever successfully converge.

Models that Combine Individual Intentionality with Group Order

Gunji: Is it possible to combine the freedom of individuals, such as their subjectivity and intentionality, with orderliness in the group they collectively comprise? This is an interesting problem, one for which modelling the movements of groups of animals can provide some useful insights.



Yukio-Pegio Gunji, Ph.D.

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He obtained a Ph.D. in science from the Graduate School of Science at Tohoku University in 1987. He was appointed a Professor in the Department of Earth and Planetary Science, Faculty of Science at Kobe University in 1999 and a Professor in the Faculty of Science and Engineering, School of Fundamental Science and Engineering at Waseda University and a Professor Emeritus, Faculty of Science at Kobe University in 2014.

He has published numerous works, including "Groups are Consciousness" (PHP Institute, 2013), "Life, Indomitable" (Seidosha, 2018), "Natural-born Intelligence" (Kodansha, 2019), and "*Yattekuru*" (Igaku-Shoin, 2020). His most recent publication is "From Whence Comes the Memory of Having Once Lived in that Game World?" (Seidosha, 2022).

Flocks of starlings or schooling sardines move in a collective fashion despite apparent randomness. While modeling such movements is surprisingly difficult, in a model I devised myself that equips the individuals that make up the group with both reactive and autonomous movements, I found it was simple to replicate group behaviors such as how their movements sync up in a linear fashion under some conditions whereas in others they just circle about or suddenly scatter in all directions.

In terms of the mechanism involved, you can think of it as an expansion or contraction in the causes that drive the decisions of individuals. While people might think that achieving orderliness requires objective decisions based on an unchanging set of causes, it turns out that groups can exhibit synchronized and harmonious movement on the basis of varying factors whereby individuals make repeated autonomous decisions while also responding to external causes. This is a state of affairs in which orderliness and the breakdown of orderliness are controlled internally. It may be that we can build such systems and still be able to control them effectively.

Horry: This is the model you wrote about in your book "Groups are Consciousness."

In the case of environmental ROIC, having the coefficients set in stone would equate to an unchanging set of factors. In practice, however, we have provided dynamism by allowing them to be increased or decreased. As mentioned earlier, equipping environmental ROIC with the scalability to be used by organizations of different sizes is another feature.

Gunji: Mixing things that differ in scale may well prove interesting. The model I have been telling you about that allows for variable factors was developed out of the book "Groups are Consciousness."

Humans Have an Innate "Natural-born Intelligence"

—You spoke about how sensing and responding to external factors equates to natural-born intelligence. Could you please go into this in a little more detail?

Gunji: While people often talk about systems being "open," I believe that this is in fact a very difficult concept. We are frequently aware that the scope of our own knowledge is circumscribed and that more exists outside. This raises the question of how we link together those things that are inside and outside this scope to make a system open. The problem is that there are also "unknown unknowns" that are even farther outside of our scope of knowledge, what I distinguish as "external factors," factors that we have never even thought to consider. What is important is how we handle these.

In terms of this division into what is inside and outside of our scope of knowledge together with unknown unknowns, what we call artificial intelligence works by applying its inference capabilities to its known world. As highlighted by the frame problem*2, because addressing what is outside our scope of knowledge will get us nowhere, we bring those factors we are able to consider into the scope of what we do know and provide a solution to the problem within this context. This is first-person intelligence whereby we make logical and rational decisions about things after having first established our own scope of knowledge. This goes beyond the realm of computers as we humans also frequently deal with things in the same manner as artificial intelligence.

"Natural intelligence" is the term I use for the transformation of this first-person perspective into a third-person one, meaning a way of thinking that comes from natural science. While it might make more sense in the context of natural history, we utilize the knowledge of the outside world that we have acquired over time as we set about finding out more about our world. This is intelligence that seeks to build an objective third-person scope of knowledge.

In contrast, natural-born intelligence does not seek to build a scope of knowledge. You could call it a "one-point-fifth-person" intelligence, one that simply responds to those external factors that are so far outside our scope of knowledge that we cannot even know they exist. While putting it this way might have you thinking it is some special intellectual capability, in fact natural-born intelligence is something that humans and other animals are equipped with innately. Unfortunately, many modern-day humans tend to think like artificial intelligences and in a convoluted sort of way there is a need to get back to natural-born intelligence.

Of course, the reason I choose to study natural-born intelligence is not because I want to discredit mechanistic artificial intelligence and put my faith in the sort of intelligence that is innate in animals. Rather, it is because I am fascinated by the question of how we can incorporate the natural-born intelligence approach into mathematical models and whether we can get it to work.

How Natural-born Intelligence Routinely Creates New Things

Horry: Given that, when you talk about what is inside and outside our scope of knowledge, you are only using this to

*2 Frame problem
An important problem in artificial intelligence. Defined by cognitive scientist Patrick J. Hayes and John McCarthy, a computer scientist who was one of the founders of AI and gave the discipline its name, the problem states that: "A robot with finite information processing capacity cannot deal with all of the problems that could potentially arise in the real world."

demarcate the world that is already known, one way to sum up what you have been saying is that it is the world in which problems are able to be defined and in which there is a clear link between problem and solution. However, everyday life in the real world is not normally that clearly defined. Your mood might change unexpectedly and have you doing things you would not have anticipated doing, or you might suddenly forget things you knew or make a mistake in a simple calculation. That is what life is like for ordinary people. While people use the terms "logos" (logic) and "physis" (nature), the reason why these things happen is because the world is not made up of logic alone. There is no way to explain it other than to assume the influence of external factors of which we are unaware.

Gunji: What I talk about as "external" may be difficult to grasp, and when you think about what sort of things it might refer to, images immediately come to mind where you can draw arrows showing systematically how they relate to ourselves. However, we can only draw these arrows for things we know that we don't know, not for external unknowns. When I talk about natural-born intelligence, what I mean rather is those situations where our unconscious or subconscious self reacts to something that happens due to external factors we are unaware of.

An example in the form of a problem and solution is how, when we intuitively imagine solutions to the problem we are considering, we instead come up with something completely unrelated. The intelligence that gives rise to such things is natural-born intelligence. You can also describe it as our capacity for routinely creating new things.

The question, then, is how best to model this type of intelligence? What I have been thinking about is how we should go about handling external factors in a systematic manner.

Affirming Both, Denying Both

——The book "Intelligence Simulation Using Cellular Automata—Implementing Natural-born Intelligence" that you co-authored came out in 2021. Have models based on natural-born intelligence already been developed?

Gunji: Yes. An indirect way of describing what sort of models these are would be to say, for example, that they involve two elements: a problem and a solution. When a problem is seen as a problem it has no solution. When a solution is found, it isn't a problem any more. Which is to say, you do not normally have both at the same time. When you create a situation in which these incompatible things are simultaneously affirmed and denied, it is like a gap opens up between them and something comes in from outside to fill it.

You may think that both affirming and denying two things that cannot coexist is not logically tenable. In the real world, however, tiny changes in boundary conditions or a shift in context can cause a problem to not be a problem any more. Moreover, such boundary conditions or contexts that are exposed to external factors cannot be controlled or tinkered with. As we make our decisions in just such a world, one that is beyond our control, it is possible for such situations to arise.

Horry: Do you have a good example of where things are jointly affirmed and jointly denied?

Gunji: As I wrote about in my book "*Yattekuru*," there was a handicapped high school student who communicated with people by showing them photographs of things he liked. His mother made up a ring binder for him filled with laminated photographs of his teachers and objects such as police cars or trucks. He would go about showing these to people he met, asking "What is this?" Once the person told him what the photograph showed, he would go on to the next person. When he came up to me to show me his photographs, I started by playing the game properly, but after a couple of rounds he showed me a photograph of a police car and I answered on a whim that it was a rhinoceros beetle. He broke out in a great big smile and hugged me saying "Gunji-san!" Since then, we have been on very good terms.

What happened between us was that, as he was someone who found it difficult to speak to other people, showing photographs to get a reaction was, for him, a way of achieving the communication of which he was only barely capable. Put another way, the situation was framed as one in which the photograph represented the problem and naming the object shown was the solution.

Then I came along and told him a police car was a beetle. He showed me a photograph and I gave him an answer, so in some sense that constituted a solution. On the other hand, it was also a problem in that he must have been wondering what on earth I was talking about, meaning that "rhinoceros beetle" became both a solution and a problem at the same time. You could also take the view that what I said was no more than a nonsense reply and so it was neither a problem nor a solution.

Something being both a solution and a problem is like a Zen koan: all you can do is ponder it. Were it neither a solution nor a problem he could just ignore me for not playing the game properly. In fact, he momentarily entered a state in which the two were in a delicate balance and so was able to experience a new phase of communication. I think it was an experience he enjoyed.

Horry: In terms of the technology, I understand you are using distributed computational models in the form of cellular automata.

Gunji: Generally, simulation by a distributed computational model involves synchronized calculation. Biological processes, on the other hand, arise from large numbers of cells working in an uncoordinated way. For this reason, asynchronous calculation is occasionally used in models that simulate biology. While a variety of methods have been developed to achieve this, they mostly involve uncoordinated actions happening randomly.

However, the workings of living systems are not entirely random, with the cells able to organize among themselves in some way to achieve coordination amid all the asynchronicity. That is, coordinated and uncoordinated behavior is negated while at the same time being achieved. This was the concept that I modeled.

Daily Life is All Innovation

—While natural-born intelligence refers to the intelligence innate in living organisms, you also noted that many people have come to act like artificial intelligences. What kind of problems do you think this will cause in the future?

Gunji: If you continually repeat a cycle of framing problems like an artificial intelligence and solving them on these terms, you will eventually run up against technological limitations. In societal terms, if a certain group of people continually solves problems based on their own framing and problem definitions, the society will likely become dismissive of anything that lies outside their frame. If that happens, I will no doubt think that I am one of those being dismissed (laughs). I will likely take offence at being ignored.

We talk about how artificial intelligence can do these wonderful things, how it can work in ways that outstrip humans. How would you feel then if someone told you, "An artificial intelligence (AI) robot can appreciate food much better than you can so you don't need to eat any more"? I would think "You're kidding" and wonder how best to keep on saying so.

Horry: What Gunji-sensei is saying sounds difficult, but he is dealing with something that is very ordinary, namely the intelligence that humans possess innately. For example, it is not at all easy to get a robot to perform actions that come naturally to animals. You have to analyze the mechanisms at work and construct theories to replicate the same actions using different materials and apparatuses. He is doing much the same thing, only in his case what he is trying to replicate is intelligence. There is much that is yet to be explained about animal intelligence and the workings of nerve cells, and about the problems of awareness and perception. His theories and model of natural-born intelligence are seen as one such solution.

This means it is not about denying artificial intelligence, rather that the practical realization of natural-born intelligence could be of great significance in our society that, as a whole, has gone too far in adopting AI-like ways of thinking. It may well open up possibilities that nobody would have thought of.

—You have spoken of how natural-born intelligence routinely creates new things. Are you saying it equates to innovation?

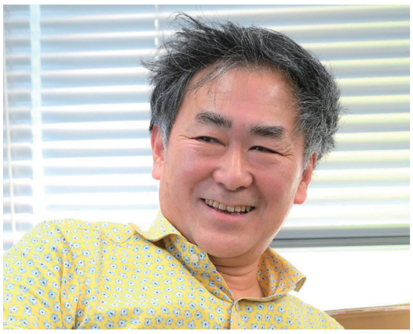
Gunji: Yes, that's right. One way of looking at it is that, rather than the world continuing as normal most of the time and only occasionally being punctuated by innovation, daily life is in fact all innovation. Rather than being a big deal, innovation is like the experience everyone has had of finding a particular food to be unexpectedly good to eat even when they are eating the same thing as usual. If we were to take a step outside our usual problem-solution framework and look at the world, I expect we might see that innovations are simple to come up with.

What Does "Specially Trained Rhinoceros Beetle" Make You Feel?

—Given that scientists and engineers are continually seeking to create new things, what do you think such people need to do to become aware of their own natural-born intelligence?

Gunji: Hmm… My laboratory website has a post about the phrase "specially trained rhinoceros beetle." "Specially," "trained," and "rhinoceros beetle." Look at these words one at a time and it is their dictionary meanings that come to mind. When you put all three together, however, I expect you find it conjures up images that are perhaps sinister, dubious, or amusing, such as some secret organization working night and day to put beetles through a rigorous training regime.

And yet, none of these images appear in the phrase itself. If you ask why they come to mind, it is because putting words in the right order causes a deep gap to open up, into which flows things from outside that you might never have expected. This deep gap is invisible. So, how do we create these invisible gaps? I believe the sensibility it entails equates to literary flair.



This is what poets do. However, they do not expect every reader to respond to their poems in the same way. You only need to open up such a gap for it to draw forth surprising responses, though they will likely be different for different readers. People may well think that those who work in the sciences are the least likely to have this literary flair, this awareness of an invisible gap. However, given that this awareness is in essence the same thing as creativity, it is important to cultivate it.

Horry: The best expression of innovation in my opinion is the "*neuen Kombinationen*" (new combinations) of Joseph Schumpeter. As with the way you put your words together, innovation results from putting things together in new combinations. This is something else I have learned from you.

Gunji: The cognitive scientist, Margaret A. Boden, divided creativity into three different categories: unfamiliar combinations of familiar ideas, the exploration of new areas, and the transformation of conceptual spaces. While Schumpeter's "new combinations" correspond to the first of these, Boden made the point that there was more to this than just putting existing things alongside one another. Because different arrangements can have completely different meanings, the creativity lies in how you chose to put them together. As in common phrases like "read between the lines," creativity comes about from successfully bringing out or grasping the value that lies outside the words themselves.

Incorporating Ways of Responding to External Factors

——How can we cultivate this sensibility?

Gunji: What I find deeply interesting is that the students of mine who produce interesting papers or good research are those who read a lot of fiction. They are also very familiar with modern literature from outside Japan. As foreign books often expose Japanese readers to different values or experiences, it maybe that this has something to do with it.

Horry: Nevertheless, I expect there is more to it than just reading books. Rather, I imagine it is to do with people's different attitudes to reading. You spoke earlier about the attitude people have that all you need to do is identify and then solve the problems facing the company or wider society, and that this approach has reached its limits. What is needed to overcome this is the ability to identify combinations that have the power to drag external factors into play.

Gunji: That human beings are adopting AI-like thinking despite their innate natural-born intelligence is, I believe, because we continue to be taught that it is a more logical and superior form of intelligence. We are trained from a young age to hone our abilities to distill things down to their essence, in the sense of taking difficult problems and asking how we can define them in such a way that they can be abstracted and simplified to obtain a solution. Releasing us from this spell will be no easy task.

While we often divide things into the humanities and sciences, in most cases, even the humanities adopt logical AI-like ways of thinking. In broad terms, artists are the only people thinking about how to get away from this. And even then, it is only some artists. As this amounts to only a very small number of people, it is no surprise how difficult it is to get the wider community to appreciate the need for natural-born intelligence and to convey to them the idea that the problems with today's technology lie in AI-like thinking.

That is why I have high hopes for you. The work you are doing provides a good practical example, and if you can make the case for the importance of external factors and natural-born intelligence from the front line of business where you are striving to achieve social innovation, it may be that things will change.

Horry: Something I particularly want to say is that the great inventions and discoveries associated with the rise of human beings, such as fire or writing or music, could only have come about as the result of natural-born intelligence. When writing, for example, was invented, it seems unlikely that the need for writing was even recognized as a problem.

While research and other forms of work always tend to be framed in terms of problems and solutions, daily life is full of situations where this approach does not apply. My favorite example of natural-born intelligence is, when thinking about the problem of what to have for dinner, instead of wondering whether to have udon noodle or soba, I choose instead to simply go home and go to sleep (laughs). I expect situations like this happen all the time. I believe we can foster innovation by taking this ordinary thinking along with ways of responding to external factors that are based on natural-born intelligence and incorporating them into all sorts of different areas.

——This has been a very interesting discussion. Thank you very much.

| **Feature** |

Energy System to Achieve Decarbonization

Energy Systems for Achieving Carbon Neutrality

The world's energy systems are approaching a crucial juncture in the transition to carbon neutrality. Along with the shift to zero-emission sources of energy and expansion in renewable energy capacity, the electricity grids need to further reinforce their ability to withstand natural disasters that are becoming increasingly severe and widespread. Considerable action is also happening on the energy demand side where the focus is on achieving more comprehensive energy efficiency and making the shift to non-fossil-fuel energy, with digital technology playing a major role in the reduction of carbon dioxide emissions. This issue of *Hitachi Review* describes how Hitachi is addressing a variety of societal challenges through work in the fields of power grids, energy solutions, and nuclear power that is improving the people's quality of life (QoL) and enhancing the corporate value of customers. This issue includes articles on the future directions and new initiatives of Hitachi's energy business in its pursuit of carbon neutrality where it seeks to deliver both security of energy supply and decarbonization.


A-WIND ENERGY wind farm in Katagami City, Akita Prefecture

FOREWORD

Policy Challenges for Achieving Carbon Neutrality

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Introduction

The perspective on measures to address global warming is undergoing a significant shift. Whereas the emphasis was once primarily on the burden these measures represent, the current global acceleration towards decarbonization has sparked a different viewpoint in Japan. Increasingly, these efforts are seen, not as a burden, but as an opportunity to create new business models and transform the country's industrial structure. A clear sign of this momentum can be seen in the emerging view that carbon pricing can be a driving force behind a green transformation (GX) of the entire socioeconomic system that will speed up the transition to carbon neutrality.

In Japan, the Act on Promotion of a Smooth Transition to a Decarbonized Growth-Oriented Economic Structure (GX Promotion Act), which authorized the issuing of GX transition bonds and introduced carbon pricing was passed on May 12, 2023 by a plenary session of the House of Representatives*1. It will see the issuing of JPY20 trillion in GX transition bonds over the next 10 years until 2032, providing support for the research, development, and adoption of new technologies for non-fossil energy (including hydrogen and ammonia, renewable energy, and nuclear power) as well as energy efficiency and carbon fixation.

The GX transition bonds are set to be repaid by the revenues generated from carbon pricing. In Japan, a global warming countermeasure tax has already been introduced. Although not directly proportional to carbon, an "implicit carbon tax" is also levied on fossil fuels, averaging around JPY 6,000 per ton of carbon[(1)]. Against a background that includes the anticipated introduction by the European Union (EU) of its Carbon Border Adjustment Mechanism (CBAM), the GX Promotion Act will introduce carbon levy and emissions trading as measures for reducing carbon emissions.

Carbon pricing will be levied on upstream suppliers such as fossil fuel importers, with introduction to begin from FY2028. The trading of emissions on a trial basis within the GX League is scheduled to get fully underway from FY2026, with auctions among electricity generation utilities to begin once renewable energy levies reach their peak*2.

While details such as the level of carbon pricing are not yet finalized, putting an appropriate price on carbon is essential if practices such as carbon capture, utilization, and storage (CCUS) are to be pursued commercially. Along with eliminating duplication with existing implicit carbon taxation such as energy efficiency regulations and energy taxes, it is also desirable to adopt systems that are

*1 This was revised by both houses of parliament before the final version was passed by the House of Representatives.

*2 In the GX Promotion Act, this is stipulated to commence in FY2033.

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neutral with regard to different technologies or forms of energy, something that can be done by making explicit the actual cost of carbon, even where it is not proportional to emissions.

This article discusses the measures to promote investment in GX that are a prerequisite for carbon pricing, looking at the key considerations through a policy-making lens.

Characteristics of GX Investment

Along with the announcement in October 2020 that it would seek to achieve carbon neutrality by 2050, Japan also indicated in April 2021 that it would adopt an additional target for FY2030 of reducing greenhouse gas emissions by 46% from their FY2013 levels while also pursuing strategies for the stretch goal of 50%.

As Japan moves toward carbon neutrality while also contributing to the achievement of this goal globally, increasing the total sum of public and private investment over the next decade to more than JPY150 trillion will require individual industries to develop the alternative practices needed to transition to carbon neutrality.

Carbon pricing is a useful tool for encouraging behavior change by those companies that have such alternative technologies for carbon neutrality available to them. For those companies or industries where such alternatives do not exist, however, simply levying a carbon price will likely result in them moving offshore ("leakage"). This is why the development of new technologies for those industries that currently lack alternative technologies requires support that is integrated with regulation.

Even once these alternative technologies have entered practical use, it is likely that while some companies will be early adopters, others will lag behind. Emissions trading is being looked at as one mechanism for controlling emissions that can mitigate the unfairness resulting from these different levels of action. Carbon neutrality is the state in which the quantities of anthropogenic emissions and sinks (absorption or elimination) are in balance at a national or global level, even though these emissions and sinks will be attributable to different actors. A requirement for this is that these different actors are able to trade these quantities in the form of credits. Given that the introduction of mechanisms for controlling emissions will likely be needed in the future, the work being done by the GX League involves establishing a voluntary emissions trading scheme for achieving targets companies have set for themselves so that it can serve as a preparatory step toward a future such scheme. It is also fair to say that the measures in the GX Promotion Act are what the GX League was aiming for in its work, extending to small and medium-sized businesses as well as large corporations.

Formulation and Evaluation of GX Investment Support Policy

The sort of technological development that comes with a high degree of uncertainty and in which private-sector companies are hesitant to invest their own funds takes years to complete and tends to require large amounts of money. Given these characteristics, measures to support GX investment call for a policy mindset that is different from what has prevailed in the past.

In simple terms, the three requirements of past policy-making have been a single-year focus, transparency, and fairness. That is, budgets must be spent within the financial year and cannot be carried over (single-year focus), provided that reviews are made public it does not matter if they are not used to inform subsequent projects (transparency), and rather than providing large amounts of investment funding to particular companies or industries, it is common practice to spread funding thinly across as many companies as possible (fairness).

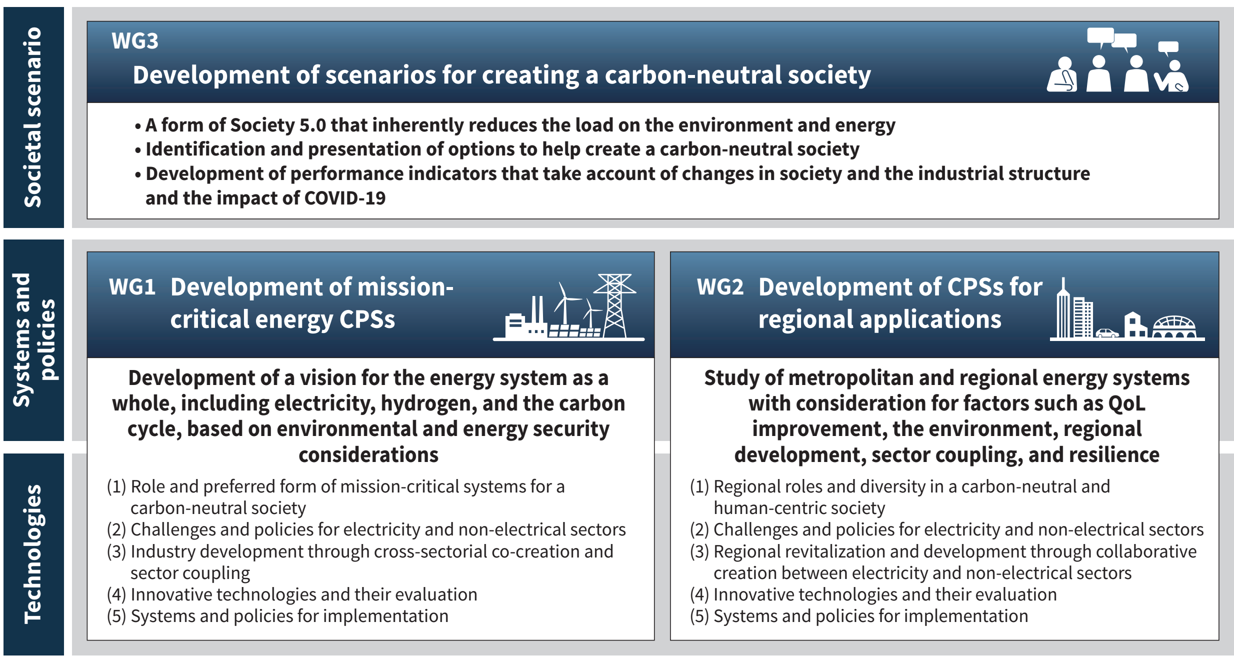
What is needed for GX investment support is to break away from these three criteria. This means providing a limited number of companies or industries with funding that runs for multiple years through periods of socioeconomic uncertainty[*3] (addressing the "fairness" and "single-year focus" criteria respectively). Given that the needs of GX will change with changing socioeconomic conditions, the policy-making stage needs to allow a certain degree of tolerance so that minor course corrections in the direction and objectives of GX investment can be made in response to the needs of society and the economy.

This is called "agile policy formulation."[(2)] To enable this, mechanisms need to be built in at the policy-making stage that allow for policies to be modified during implementation, with the collection of data in real time and appropriate evaluation practices that are not tied to the financial year. The sort of dynamic policy formulation and evaluation that provides agility is especially needed when funding GX investment that is expected to run for five years or more. Work on this sort of evaluation should facilitate action on digital transformation (DX). This approach to GX should also help avoid the tacit public demand for "policy infallibility," (the notion that targets, once set, should never be changed) and undo the spells that this casts (to address the past issues with "transparency").

Programs for GX Investment Support

Another issue that arises when providing support for GX investment is the question of what criteria and key performance indicators (KPIs) should be applied to policy implementation when there is a high level of uncertainty and a need for agility. One possibility is to base responsibility for

*3 The applies not only to GX, but also to other corporate assistance such as semiconductor industry support for reasons of economic security.



WG: working group CPS: cyber-physical system QoL: quality of life

Phase 2 Mission of Hitachi-UTokyo Laboratory

policy outcomes on results, for example, as outcomes may be different depending on external circumstances such as market conditions, domestic and overseas technology competition, or personnel changes. It has already been noted that the use of results-based criteria to evaluate such projects, which are not easily replicable, poses many problems(3).

Consider an example in which the criterion used is improvement in energy productivity. In such an example, it may be difficult to distinguish energy productivity improvement from a decline in labor productivity or the movement offshore of high-added-value manufacturing. Likewise, if profitability is used instead, the risk is a failure to recognize the benefits of decarbonization investments that take a long time to be reflected in the bottom line, causing such investments to stall.

Basing evaluation on inputs instead of these outcomes or outputs, on the other hand, is prone to moral hazards and it will likely be difficult to recognize whether GX investment is really being done on a best-effort basis. Given the difficulty of evaluating support policies based on the investment process, it suggests that more work needs to go into finding new policy formulation and assessment practices for the monitoring and evaluation of GX investment. If evaluation based on outputs and outcomes is difficult, it may be that this calls for the use of market assessment of GX investment. Once we have overcome the issues of single-year focus, transparency, and fairness, we will need to start talking about forms of policy formulation and evaluation that do not rely on policy infallibility.

Achieving Carbon Neutrality in 2050

On March 24, 2023, Hitachi-UTokyo Laboratory published version 5 of its proposal entitled, "Toward Realizing Energy Systems to Support Society 5.0"(4). The seven-chapter, 63-page proposal lists a total of 18 declarations under the three headings of geopolitical change, global action on decarbonization, and specific national or regional circumstances.

Making a just transition that also encompasses employment will not only that we develop a clear understanding of what sort of energy transition we will be undertaking on our path to carbon neutrality in 2050. It is also crucial that action be taken around the world on finding ways to encourage behavior change in consumers by addressing greenhouse gas emissions on a consumption basis, instead of a production basis. An essential consideration when it comes to achieving this will be greater transparency regarding greenhouse gases in the supply chain, with the use of digitalization to determine carbon footprints.

If the goal of JPY150 trillion in public and private investment is to be achieved over the coming decade, we will need to look carefully at the fundamentals, namely, the type of policies we adopt and how we go about evaluating integrated policy packages that cover both regulation and support. With the recent passing of the GX Promotion Act marking a shift to the policy implementation phase, there is potential for Japan to become a source of the core technological and policy infrastructure that will lead to the whole world changing its behavior to enable carbon neutrality in 2050, engaging with the Asia region as we do so and remembering the importance of treating evaluation as an integral part of policy formulation. Indeed, this is a time when Hitachi-UTokyo Laboratory needs to be consolidating the wisdom of Japanese industry, government, and academia so as to play a leading role in GX.

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TRENDS

Rethinking Current Practices to Enable a Sustainable Future

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Mary is the Co-Director of the Hitachi and Imperial Centre for Decarbonisation and Natural Climate Solutions. At Imperial, she is Professor of Materials Science and Nanotechnology and leads a large interdisciplinary group focused on understanding nanoscale materials, and nanoscale interfaces in and between materials and their environments. She has a particular interest in the development of operando approaches and has pioneered nanoscale methods in synchrotron science. She was elected Fellow of the Royal Academy of Engineering in 2015 and is a Fellow IoM3 and of the Institute of Corrosion. She is also Armourers and Brasiers' Chair for Materials Science and holds a CBE for her career-long contributions in this field.

The UK's Action on Decarbonization

Many countries and regions have declared their intention to reach zero carbon or carbon neutrality by 2050 or 2060. Meanwhile, environmental problems have been a longstanding concern for the nations of Europe, with specific policies and schemes for investment in carbon neutrality making the region a leader in global decarbonization. What are the key considerations when it comes to achieving carbon neutrality? Also, as an island nation in Europe, can you talk about what the UK, in particular, is doing?

The European nations are indeed taking practical action on carbon neutrality, having adopted a variety of policies and regulations aimed at achieving this ambitious goal. Unfortunately, the path to carbon neutrality by 2050 is complex and there is no "one size fits all." Different countries are pursuing drastically different strategies. Germany, for example, has put a lot of effort into solar power whereas in France there is a longstanding commitment to nuclear power. As an island nation, the UK is making use of offshore wind power generation. Offshore wind has expanded considerably over the past decade, to the extent that it often now accounts for as much as 50% of the total electric power supplied to the UK grid. While this represents major progress, it is still not enough to get us to carbon neutrality. More action is needed.

While nuclear energy currently supplies approximately 15% of the electric power to the UK grid, our existing nuclear plants are reaching the end of life and it remains a subject of much debate whether the construction of new plants is needed to maintain the security of energy supplies. Another key issue is that major upgrades to the electricity distribution (grid) infrastructure will be needed if we are to transition to 100% renewable energy. Imperial College London is working as part of the Global Power Systems Transformation Consortium* on this.

MISSION ZERO—Independent Review of Net Zero was published in January 2023 by Chris Skidmore, the former Minister for Energy and Clean Growth. It highlights a variety of technological issues specific to the UK that will need to be addressed in the future, also laying out policy measures for making the transition to carbon neutrality. In business, for example, it asks what planning will be needed from the private sector as it factors regulatory considerations into the research and development of technology. As well as addressing policies and frameworks for supporting the transition that relate to the general public, such as what standards to set for the construction of new homes and how existing homes can be improved, the review also touches on critical technical questions regarding the use of solar power for electrification, the use of carbon capture and storage (CCS), and natural sources of energy. On the supply side, issues such as the full electrification of transportation and the supply of industrial and domestic heat are also covered, along with the question of how to shift to a hydrogen-based economy. On the demand side, a key issue is how the system can be made more efficient in response to demand.

While these many and varied opportunities exist for decarbonizing society, it also seems likely that the final stages of decarbonization will require CCS in some form, meaning that progress is needed on the associated technologies. We need to accelerate technology development and innovation to make the transition to a carbon-neutral society while also proceeding in a way that all regions onboard. Achieving this will require appropriate global investments and incentives.

* A consortium that brings together the knowledge of system operators, manufacturers, electric utilities, standardization organizations, research institutes, etc., with the goal of operating the world's power grids on 100% renewable energy.

Decarbonization policy in the UK has prioritized industrial heat and domestic heating demand. What specific actions are you taking in this area?

With the dramatic increases in the price of natural gas in response to the war in Ukraine, large increases in the cost of domestic electricity have made this a very political issue and considerations around energy security and fuel poverty need to be factored into the "use of heat." The UK has a large number of poorly insulated homes with low heat efficiency, the majority of them heated by gas boilers. This is one of the key challenges we need to prioritize on our way to achieving decarbonization. A variety of policies for improving home insulation have been introduced over the past decade, with limited success. Heat pumps represent one promising solution and switching from gas boilers to less energy-hungry heat pumps has the potential to improve both people's lives and energy demand without compromising the living environment in their homes. While the UK government offers support to reduce the cost of installing heat pumps, two major obstacles to their wider adoption still remain. The first is that the cost to install remains higher in most cases than for a gas boiler. The second is a shortage of people with the requisite installation and maintenance skills. To address this, steps are being taken to drive the cost of heat pump installation down to the same level as gas boilers, with a lot of effort going into skills training at private-sector energy companies. In the future, I hope to see the shift to heat pumps being led by new-build homes, with regulations preventing the installation of gas boilers in new dwellings.

Rental housing is another focus of debate, key questions being who is responsible and who will bear the costs of change? As these are questions that span society, politics, and economics, everyone needs to be thinking about the respective roles that should be played by government, private companies, and individuals if we are to achieve an equitable transition to carbon neutrality. Meanwhile, although heating is probably not the best use for green hydrogen, this is a matter that will need to be addressed over the longer term given that, as yet, neither the technology nor the regulatory framework is adequately in place.

Similarly, technological innovation is also needed for industrial heating, including for the potential use of hydrogen, as will scale up of CCS to offset the carbon dioxide (CO_2) emissions from steelmaking and other heavy industry during the transition.

Rethinking Current Practices to Enable a Sustainable Future

It is recognized that the achievement of a sustainable society calls for action not only on reducing CO_2 emissions, but also on a range of other issues, including biodiversity, reducing food losses, and education. What do you see as the key points to consider when undertaking these actions?

Under the framework of the Imperial Zero Pollution Initiative, we are seeking to change how we do research and teaching at Imperial College London in order to address a wider range of environmental problems beyond focusing solely on carbon. Confronting the three great threats to the global environment of climate change, biodiversity loss, and chemical pollution calls for systems-level thinking, treating these issues in a holistic framework that looks at interdependencies. Part of this is the need always to be thinking about the choices we make and the consequences they bring.

If we replace petrol and diesel cars with electric vehicles (EVs), for example, what will happen to the pollution caused by mining the lithium and cobalt in different parts of the globe for batteries? What about the problems of road use and the particulates released by tires? What influence will this have on the health of people and the environment? A key point is to consider, as we transition to a net zero society, the potential for unintended consequences. The risk if we fail to consider the system as a whole and focus instead solely on reducing exhaust gas and CO_2 emissions is that we will end up damaging the environment in different ways.

Issues also arise regarding our ability to recycle the diverse resources needed for the deployment of new technologies. If we are to create a truly sustainable society, we need to be paying close attention to the use and reuse of finite resources. Understanding how we design for recycling, and change societal behaviour is critical to this.

Something we should never forget is that people lie at the heart of every system. It is vitally important when considering the adoption of a new technology that we ask whether or not it will be accepted by the public and how it will impact people individually and collectively. The participation of all sectors of the public is a prerequisite for achieving a society that is decarbonized, sustainable, and equitable. Achieving sustainable economic growth will require us to rethink the responsibilities of individuals, companies, and nations for environmental pollution as well as the nature of growth, driving a shift in both people and nations away from behaviors inspired by our existing consumer economy.

While our world confronts a diverse multitude of challenges, we can choose to view these challenges as a chance to build a different future. This involves rethinking everything in order to create clean and livable cities together with sustainable and secure energy systems. In effect, it means designing the future. While this process may well involve disruptive creation, I hope that it will also bring protection for the environment and a healthier and more prosperous life for people.

Rather than thinking only of the present, you are saying that we need to create a truly sustainable world by establishing a circular economy and recycling businesses that look to the future. Thank you for your time today.

ACTIVITIES 1

Helping Fleets Achieve Accelerated Electrification

Optimise Prime Initiative in the UK

Ben Kinrade | Colm Gallagher | Paula Jach | Priya Nagra

Optimise Prime was the world's largest commercial electric vehicle innovation project in the UK, which aimed to accelerate the transition of fleets to zero emission vehicles by reducing barriers that could be caused by electricity distribution networks. Over the last four years, Hitachi has led a group of partners, including major UK fleets, electricity networks and technology providers, in order to gather data on the usage of commercial EVs and trial new methods that will reduce impact on electricity infrastructure. The project has recently concluded, exceeding its original goals by involving over 8,000 EVs across the UK. The data gathered will help power networks and local authorities plan to meet future EV charging demand, while the project also proved that new connection and demand-side-response products will help fleets and networks electrify cost effectively. Hitachi is building on the project's findings to provide services that help fleet operators accelerate their electrification.

Introduction

Poor air quality in cities is a significant driver of early mortality—in 2019 it was estimated that around 4,000 lives were lost each year in London as a result toxic air, primarily emitted by road transport(1). To combat this, recent years have seen significant policy changes to reduce local air quality issues, such as congestion charging and the Ultra-Low Emissions Zone, coupled with national and international efforts to achieve net zero transportation. To comply with these requirements, as well as corporate sustainability goals, fleet managers must manage a significant transition to new vehicle technologies.

The wider availability of electric vehicles (EVs) is now allowing more commercial fleets to electrify, with the global EV100 consortium recently announcing that its members have over 400,000 EVs on the road(2). This rapid transition poses significant challenges for local authorities, infrastructure operators and electricity distributors, who need to ensure that infrastructure is in place to support EV growth while managing cost incurred by the public. To overcome these challenges, a partnership approach is required—Hitachi Europe and Hitachi Vantara brought together a consortium including electricity distributors UK Power Networks and Scottish and Southern Electricity Networks, major vehicle operators Royal Mail, Centrica, and Uber, and leasing company Novuna Vehicle Solutions to form Optimise Prime. The project's objectives were to gather quantitative data on large scale EV operations while trialing innovative techniques to limit the impact of increased electrical demand on the electricity network. The aims of Optimise Prime were introduced in *Hitachi Review* Vol. 69, No. 4(3) published in 2020 and this article provides an update on the findings from the project and how Hitachi is using these learnings to develop solutions for the electrification of fleets.

How Commercial Fleets Are Adopting Electric Vehicles

Data from over 8,000 EVs were collected and analyzed throughout the Optimise Prime trials. This included telemetry and charging data from light commercial vehicles operated by Royal Mail and British Gas, in addition to trip data private hire vehicles (PHVs) operating on the Uber platform. Study of this data highlighted the range of different journey patterns amongst the fleets. While British Gas's return-to-home fleet generally started charging in the early evening, when demand on the electricity network is highest, Royal Mail's postal delivery fleet often charged in the early afternoon or late evening (see Figure 1), depending on shift patterns at specific depots. PHVs charged throughout the day, however their demand peaked overnight.

Understanding these patterns is useful to the network operator, who may presume that all new EV load impacts their peak demand, potentially triggering network upgrades. With accurate charging data, realistic load growth predictions for their networks can be created, avoiding unnecessary network infrastructure upgrades. This keeps costs down for electricity bill payers.

The analysis of data helped identify seasonal changes in demand, caused by both vehicle efficiency and variations in vehicle activity—for example in the British Gas fleet, vans needed 30% more energy overall in the winter with range per kWh reducing by 7% for every 10°C decrease in temperature.

Future demand growth was forecast based on the data gathered by the project and the electrification plans of the partner fleets. These forecasts for each fleet revealed insights into how demand for electricity and charging infrastructure is likely to develop as the transition to EVs continues to accelerate.

Once all Uber vehicles in Greater London are electrified it was estimated that, if drivers opt for 7 kW charging near their homes, an additional 33,600 chargers may be needed throughout Greater London. As the capacity of EV batteries increases it's expected that demand will shift, with less 'on-shift' charging required during the day, and as the rollout moves from 'first adopters' to all drivers, the locations where charging infrastructure is needed will change (see Figure 2).

New Technology and Commercial Models Can Reduce Impact on Electricity Distribution Networks

Smart charging, where charging times and speeds are altered in order to reduce cost or manage load, has been

Figure 1 | Unmanaged Load at Royal Mail Depots

The figure shows how peak load often falls outside the electricity network's evening peak.

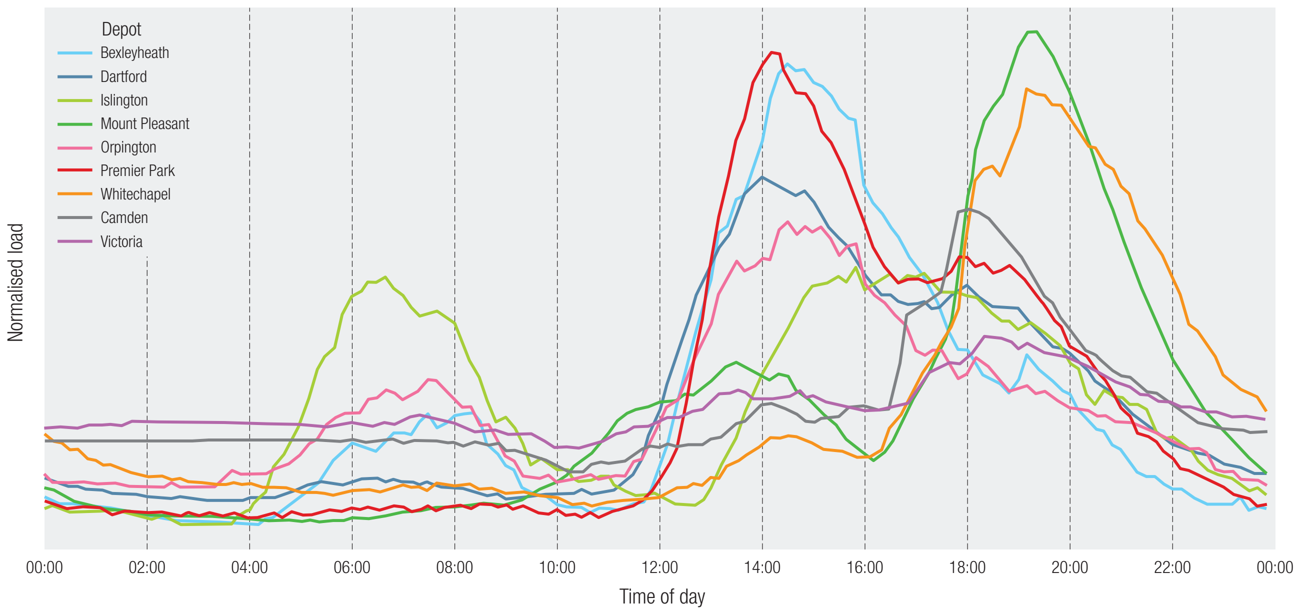
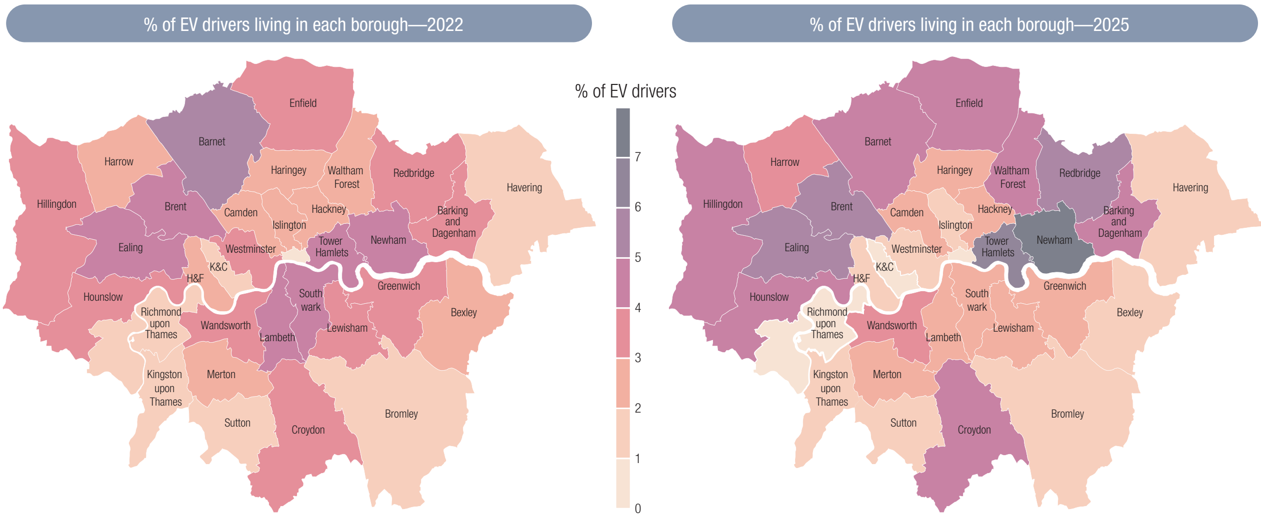


Figure 2 | Expected Change in Relative Demand for EV Chargers across London 2022–2025



EV: electric vehicle

identified as a key technology in managing the impact of electric vehicles. However, if all assets are following the same price signals to minimize cost, it may increase load peaks. Depending on local constraints this may create a greater problem for the distribution network and it is useful for a network operator to have a range of tools to influence load. Hitachi implemented charging control systems at nine Royal Mail depots across London to test several different methods of controlling and incentivizing smart charging (see Figure 3).

Flexibility services, where the network operator makes a payment to a customer in return for reducing load at peak times, are an established tool for network management, often utilized by companies with large industrial loads that can be controlled. Hitachi aggregated the predicted load from EVs charging at each depot and offered demand response services to the network operator. When an offer was accepted, the charging control system reduced the capacity available to EVs charging at the depot.

The same system was also able to manage load over a longer term by managing the EV demand in line with a new connection product called a 'profiled connection.' This allowed demand limits to vary every 30 minutes of the day and dynamically allocate capacity for EV charging in line with the available capacity on the network. This contrasts with a typical, fixed allocated capacity that can lead to underutilized network infrastructure.

Optimise Prime successfully proved the technical feasibility of both flexibility services and profiled connections.

Figure 3 | EVs Charging at Royal Mail's Mount Pleasant Mail Centre in Central London

However, the project also identified limitations that must be considered when designing solutions of this type. For example, the volume and timing of charging is much more difficult to predict at smaller depots, making the accurate provision of flexibility challenging. With profiled connections, the EV load must be sufficiently large to counter any variance in background load, and profiles may need to be updated periodically to account for seasonal variations.

Understanding the Views of Drivers and the Barriers Faced by Businesses

In addition to the technical trials, the project undertook analysis of financial and behavioral factors that may impact how quickly fleets electrify.

An understanding of the economics of fleet electrification is crucial for fleets, network operators, and other stakeholders, as the cost-benefit analysis impacts upon how quickly fleets will electrify. The project's financial models explore the costs faced by fleets, taking into account the impacts of recent changes, such as variations in electricity, fuel, and vehicle prices and the effects of government policies.

Financial motivators are not the only value consideration when fleet managers choose to switch their fleets to EV. Environmental and reputational benefits are a key consideration, as is ensuring that business can carry on as usual and that drivers are happy with their new working environment. Optimise Prime explored behavioral aspects of the transition to EV by collecting over 3,000 questionnaire responses from drivers and managers across 8 fleets. The surveys included questions on adoption, barriers and enablers, user experience and changes in their experience over time. While the results showed an overwhelmingly positive opinion of EVs, they highlighted pain points, including concerns over charger accessibility, which fleets should consider when planning infrastructure rollout and driver education.

The Impact of Optimise Prime

As a project that spans the domains of transport and energy, Optimise Prime has created a wide range of benefits for a breadth of stakeholders. The project's final event, held in London in January 2023, invited participants from throughout the fleet and energy industries to hear the project's results and participate in a panel discussion with Optimise Prime fleet managers (see Figure 4).

Optimise Prime set out to quantify and minimize the network impact of EVs while developing the value proposition and technical requirements for fleets and distribution network operators (DNOs). This has been achieved, with the project identifying significant potential savings for fleets that can be achieved by implementing smart charging and quantifying revenues available from flexibility services. The outcomes from Optimise Prime, including a substantial dataset, have been made public so that other organizations can benefit from the project's findings[4].

Hitachi's Solutions for Fleet Decarbonisation

Hitachi ZeroCarbon, a division of Hitachi Europe Limited, is responsible for developing solutions that help fleet operators electrify and reach net zero. Lessons learnt from Optimise Prime, and the technologies developed as part of the project are being implemented to help customers electrify their fleets economically. As an example of this, Hitachi has entered into a strategic partnership with First Bus, one of the largest bus operators in the UK, and has implemented smart charging software to control site demand, manage battery health, and offer the charging infrastructure at First's Glasgow depot to third-party fleets, creating new revenue streams. Hitachi is working across Europe to deliver charging and energy management

Figure 4 | **Panel Session at Project Close Down Event**

solutions, together with managed services and battery financing, which enable customers to meet their carbon reduction goals.

Conclusions

Optimise Prime has shown how the use of data and advanced charging control techniques can provide benefits to both electricity distribution networks and fleet customers, reducing costs of electrification. In turn, this reduction in costs can encourage companies to transition to EVs more rapidly, bringing substantial environmental benefits.

Hitachi ZeroCarbon is helping fleet managers benefit from the opportunities that EVs bring to reduce companies' impact on the environment. With the findings from Optimise Prime, and the technology developed as part of the trials, Hitachi offers end-to-end energy and mobility solutions that make that transition achievable and cost effective.

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Hitachi Zero Carbon, Hitachi Europe Ltd. *Current work and research:* Development and implementation of projects and solutions for the decarbonization of commercial vehicle fleets as a Senior Business Analyst.

Colm Gallagher, Ph.D.

Hitachi Zero Carbon, Hitachi Europe Ltd. *Current work and research:* Development of smart, data-driven solutions that enable fleet decarbonization at scale and least-cost for Hitachi ZeroCarbon's customers as a Chief Data Scientist.

Paula Jach

Hitachi Zero Carbon, Hitachi Europe Ltd. *Current work and research:* Several fleet decarbonization projects for Hitachi ZeroCarbon as a Business Analyst, supporting operational teams with EV charging analysis.

Priya Nagra

Hitachi Zero Carbon, Hitachi Europe Ltd. *Current work and research:* Customer Strategy team within Hitachi ZeroCarbon as a Business Modelling Analyst, building on knowledge gained from Optimise Prime to deliver actionable and innovative strategies for businesses seeking to electrify their fleets and decarbonize their operations.

ACTIVITIES 2

Achieving Carbon Neutrality in 2050

Policies and Technologies Needed for GX

Satoru Katsuno
President of the Institute of Electrical Engineers of Japan (at the time of the interview)
Chairman of the Board of Directors, Chubu Electric Power Co., Inc.

Sumiko Takeuchi
Member of the Board of Directors, International Environment and Economy Institute
Specially Appointed Professor, Tohoku University
Joint Representative, U3Innovations LLC

Moderator
Tatsuya Yamada
Division General Manager, Energy Business Planning & Strategy Division, Energy Business Division, Hitachi, Ltd.

The circumstances surrounding energy are going through major changes, including worsening climate change and emerging geopolitical risk. As the impact of climate change on people's lives and corporate activity is becoming increasingly significant, efforts are required both for CO_2 emission reductions to address climate change and action to ensure security and the stability of energy supplies to avoid public and business disruption. What sort of measures will we need to adopt in relation to energy if we are to achieve the overarching goal of carbon neutrality? *Hitachi Review* invited Satoru Katsuno, the 109th President of the Institute of Electrical Engineers of Japan, and Sumiko Takeuchi, a Member of the Board of Directors at the International Environment and Economy Institute and a Joint Representative of U3Innovations LLC, to share their visions for the decarbonization of society and to discuss specific measures for promoting and implementing GX.

Rapidly Changing Business Environment for Energy

Yamada: The topic for today is the green transformation (GX) for achieving carbon neutrality by 2050 and the policies and technologies that this will require. Confronted as we are by a variety of unexpected developments, what should we be doing to achieve carbon neutrality by 2050 in a way that avoids disrupting people's lives and maintains business and economic stability while also ensuring security and a stable energy supply? As you are both well acquainted with the energy industry in Japan, I would like to hear what you have to say on this subject.

Starting with the business environment for energy, the world has changed considerably since Russia launched its invasion of Ukraine in February 2022. Please give me your thoughts on recent developments and your outlook for the future.

Katsuno: Former Prime Minister Suga announced the goal of carbon neutrality by 2050 in his general policy speech in October 2020. Subsequently, in April 2021, the Global Warming Prevention Headquarters announced the specific goal of reducing FY2030 greenhouse gas emissions by 46% from their FY2013 level, which is to be accompanied by the pursuit of strategies for a stretch goal of 50%. As a national commitment, this carries a lot of weight, with companies and industry also accelerating their action on carbon neutrality. While this was happening, however, investment in the upstream end of the energy industry (exploration, development, and production) has stalled and there has been no increase in total fuel supplies. Given that demand continues to increase, primarily in Asia, this has set energy prices on a rising trend, one that is overlaid by the impact of the Russian invasion of Ukraine. Everyone appreciates that stable energy prices are just as important as a stable supply, and with all this has come greater interest in the issue of economic security. Changes in the world order that demonstrate the indivisibility of politics and economics are a reminder that it is up to us to protect our own economy and society.

While reforms to the power system are being accompanied by experimentation with a variety of market development and market design initiatives, the end result has been that power generation plants with poor utilization have found it difficult to cover their fixed costs and have in some cases been taken out of service. The recent rise in energy prices can be attributed to a combination of factors, with both a tightening in the supply and demand situation for fuel and a shortage of generation equipment.

One option that cannot be ignored when addressing these challenges is the restarting of nuclear power generation. While ensuring safety is a key prerequisite, I believe this will be a vital factor in the pursuit of GX if we are to achieve energy security, stability of supply, and energy price stability.

Satoru Katsuno

President of the Institute of Electrical Engineers of Japan (at the time of the interview)

Chairman of the Board of Directors, Chubu Electric Power Co., Inc.

Joined Chubu Electric Power Co., Inc. in 1977 after graduating from the Department of Electrical Engineering, the Faculty of Engineering, Keio University. Following roles as General Manager of the Okazaki Regional Office; General Manager of the Tokyo Office; Representative Director, Executive Vice President, and General Manager of the Corporate Planning & Strategy Division; and President & Director, he was appointed Chairman of the Board of Directors in 2020. Other appointments include Chairman of the Federation of Electric Power Companies and President of the Institute of Electrical Engineers of Japan.

Takeuchi: I would like to start by making three points about our current energy environment.

The first is the difference in how people think about climate change policy and about energy policy. Energy policy is ultimately a practical matter and its planning is forward-looking, taking account of current circumstances, while planning 10 or 20 years into the future. Climate change policy, in contrast, is nothing less than societal reform and calls for wide-ranging innovation. As projecting ahead based on a continuation of current trends will not lead to major changes, climate change policy instead involves developing a vision for the sort of future we want and then backcasting from there. While it may be possible to reconcile these approaches over timeframes in the order of a hundred years, trying to do so for 2030 or 2050 will only result in plans that are out of step.

Along with the Ukraine crisis, the last year has seen a jump in energy prices that could justifiably be called the third great oil crisis. Whereas "climate change" used to be one of the terms most commonly heard on the lips of European and other national leaders, "energy security" has taken its place. Nevertheless, when I attended the 27th United Nations Climate Change Conference of the Parties (COP27) last year, it wasn't as if the gathered world leaders had stopped waving the flag for climate change. I do feel, though, that they are struggling with the disconnect that arises from the different ways of thinking about climate change and energy policy, and from their different timeframes.

The second point is that nations around the world are looking at climate change in terms of their own national growth strategies and there is a growing tendency to see it as a means of seizing a competitive advantage. The USA's Inflation Reduction Act, for example, is explicitly intended to support industries with a role in addressing climate change and it is unambiguously targeted at achieving sustainable growth and economic security by directing large subsidies at these sectors. Companies, too, need to think strategically about how they can turn climate change into an opportunity for growth.

The last point is a response, from an energy policy perspective, to the issue Katsuno-san raised earlier about how a large number of reforms are happening at the same time. These include the deregulation and adoption of market principles in the power system, growth in renewable energy, and fundamental reform of nuclear safety regulations. It has been pointed out that the way that countries around the world, Japan included, have gone about reform in the

Sumiko Takeuchi
Member of the Board of Directors, International Environment and Economy Institute
Specially Appointed Professor, Tohoku University
Joint Representative, U3Innovations LLC
Obtained a doctorate in engineering from the School of Engineering, the University of Tokyo in 2022. After graduating from the Faculty of Law, Keio University, she worked primarily in the environmental division of Tokyo Electric Power Company before setting up on her own. She has worked as a researcher at a few think tanks and sat on numerous government committees, including the Cabinet Office's Council for Regulatory Reform and the GX Implementation Council. Major publications include "The Truth of Energy Policies" (Wedge), "Energy Industry in 2050—Game Change to Utility 3.0" and "Energy Industry Strategy for 2030" (Nihon Keizai Shimbun, Inc.), "Electrical Collapse: The Strategy-devoid National Energy Defeat" (Nihon Keizai Shimbun, Inc.). She is a regular member of the Japan Society of Public Utility Economics.

past has made matters worse when that reform has coincided with an expansion in renewable energy, with a lack of investment in the generation capacity needed to ensure stability of supply. By leaving operators with no choice but to shrink margins for securing electricity supply, reforms have exacerbated the problem of how to maintain stability of supply. While past practice has been underpinned by a rate-of-return regulation that has enabled private-sector electricity utilities to bear some of the burden, the advantage in a competitive market goes to those operators that are prepared to shave the safety margins they keep for times when supply and demand are tight. Along with the securing of generation capacity, deregulation reforms have also impacted long-term contracts for fuel and I believe there is an urgent need to reassess the balance of risk between private-sector companies and the government.

Challenges for Japan Highlighted by GX Implementation Council

Yamada: To make progress on GX, the Japanese government established the GX Implementation Council chaired by Prime Minister Kishida in July 2022. The council put together a guiding strategy in December. As members of the council, the two of you participated in those discussions. Can you tell us a little about the matters discussed?

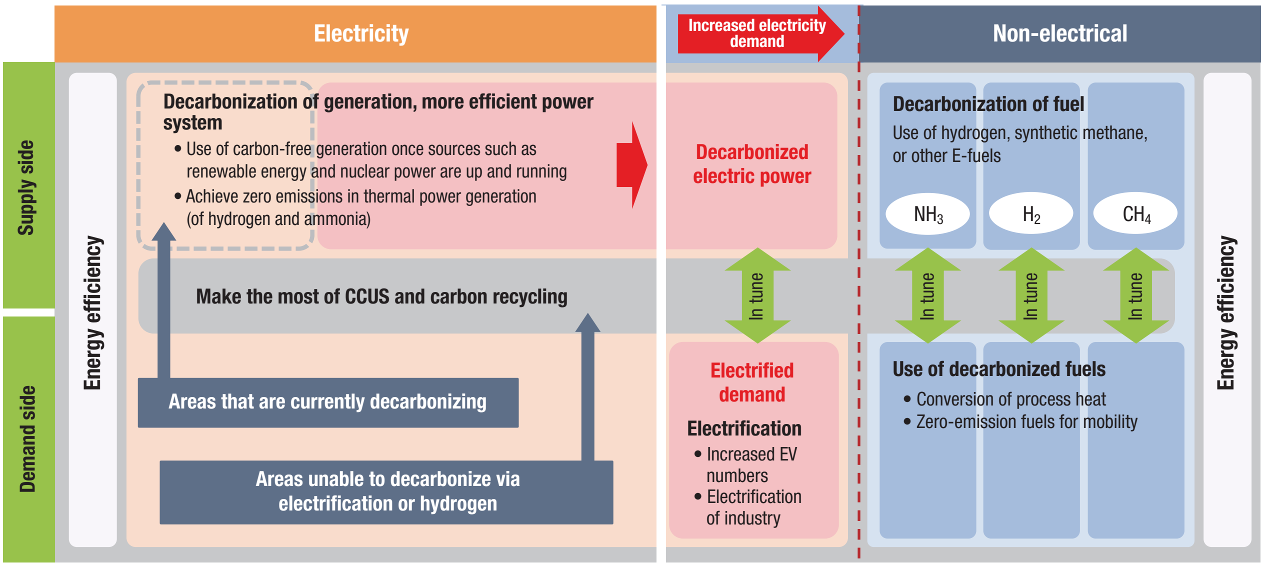
Katsuno: Rebuilding stable supply mechanisms was a major topic. That is, as we move toward achieving carbon neutrality, it is extremely important that we develop realistic plans that will maintain a stable supply through the transition process. The transition needs to be one in which disruptive innovations are combined in a way that gives us an uninterrupted path to carbon neutrality. To this end, the GX Implementation Council has highlighted the need to produce a roadmap to 2050 (overall plan and sector-specific plans), define milestones, and decarbonize in a way that keeps energy suppliers and consumers in tune (see Figure 1). While I expect that work toward carbon neutrality will include progress on energy efficiency and electrification, this still leaves the non-electrical sector for which such measures are insufficient. While it will take investment to decarbonize in a way that also encompasses these non-electrical sectors, questions remain as to how we can optimize the timeline of investment, returns, and losses, including those losses that occur along the way. This optimization needs to be undertaken at the corporate, industry, and national levels.

In addition to the use of nuclear power and a more significant role for renewable energy, the use of thermal power generation to balance supply and demand fluctuations will also play an important role in the power supply. As making the shift to carbon neutrality without compromising stability of supply will involve greater use of lower carbon fuels and the adoption of zero-emission practices, I also believe that the path Japan should be taking is one that includes our exporting the resulting low-carbon technologies to the world. I see a need here for strategic action, this also being a matter of economic security and how we can ensure that Japan maintains its presence and strategic necessity in global supply chains.

A major challenge that I have already touched on is the use of nuclear power. Unless we embark seriously on this work right now, the human resources, technology,

Figure 1 | How to Transition to Carbon Neutrality

Along with supply-side decarbonization, there is also a need for complimentary structural changes on the demand side. What is needed is a transition that keeps consumers and suppliers in tune.



Source: Fourth GX Implementation Council, Documents supplied by Satoru Katsuno of Chubu Electric Power Co., Inc. (Nov. 2022)

CCUS: carbon capture, utilization, and storage EV: electric vehicle E-fuel: electrofuel NH_3: ammonia H_2: hydrogen CH_4: methane

production base, and other infrastructure will not be ready when needed. It is essential that we restart work immediately, not only on advanced light water reactors, but also small modular reactors (SMRs), fast reactors, high-temperature gas-cooled reactors, and fusion. This is a challenge that I believe industry needs to take up for itself, with ambitious plans and targets for research and development.

Takeuchi: The topics discussed in the earlier and latter half of the GX Implementation Council were very different. The earlier half was dominated by talk about a redesign of deregulation and the rebuilding of the nuclear power industry, while the latter half addressed GX investment and carbon pricing in terms of how such investment can be encouraged.

A broad consensus was achieved on the need for nuclear power as well as on the redesign of deregulation. With a population of more than 120 million and an industry structure heavily focused on manufacturing, annual demand for electricity in Japan is around one trillion kWh. Given our small land area, 70% of which is mountainous, use of renewable energy alone is simply not a viable option for supplying that level of electricity demand. I believe that Prime Minister Kishida conveyed an important message when he used the word "and" when talking about "renewable and nuclear energy." If we are to take advantage of nuclear power, however, a more in-depth debate will be needed on how business and industry can be put on a sound footing, with it being essential that a comprehensive operating environment be put in place that covers

Moderator

Tatsuya Yamada

Division General Manager, Energy Business Planning & Strategy Division, Energy Business Division, Hitachi, Ltd.

Joined Hokuriku Electric Power Company in 1987. After secondment to the Institute of Energy Economics, Japan in 1998, he joined Hitachi, Ltd. in 2002. Having been appointed Director of the Management Planning Office at the Strategy Planning Division in 2014, Senior Manager of the Business Planning Division at the Energy Solution Business Unit in 2016, and General Manager of the Business Planning Division at the New Age Energy Business Co-create Division in 2019, he was appointed to his current position in 2020. He is engaged in policy proposal work relating to the energy business. He is Vice President of the Institute of Electrical Engineers of Japan and a regular member of the Japan Society of Public Utility Economics.

the relationships and other forms of cooperation with the communities where the plants are located, as well as providing better and more efficient compensation programs and safety regulation.

Yamada: It is a situation where a lot of things are happening at the same time, making the answers more complex. You might settle on one approach as being the best, but then the underlying circumstances could change, making alternative approaches very different and changing the outcomes. Nuclear power serves as a classic example. It used to operate safely in an environment protected by regulations, but that entire basis has been undermined. If circumstances then change in a way that calls for it to be restarted, it may be that regulations is unable to keep up.

Takeuchi: I am conscious of a lack of comprehensive debate on energy policy. While energy policy is said to be about simultaneously achieving "energy security, economic efficiency, environment, and safety" (3E+S), this still leaves us with a trilemma over where the primary focus should be. In this situation, where satisfying one requirement compromises another, you can make the case that people have failed to take a broad view and have paid insufficient attention to risk management. Looking at the situation in broad terms is extremely important.

Japan, by nature, is highly constrained in its energy policy options, leaving little scope to debate those options that are available. While I believe that communicating energy policy to the public to gain its understanding is at the heart of the matter, the truth is that this is a responsibility our government has continually evaded in the past.

Katsuno: As Japan faces diverse challenges, but it resources are limited, so it seems important to me that we clarify our priorities and gain a public consensus. This is not limited to energy, so instead of simply saying 'yes' or 'no' to specifics, we need to be considering the issue in its entirety.

Carbon Neutrality and Societal Change Brought about by Digitalization

Yamada: Takeuchi-san, in your use of the concept of Utility 3.0 to depict how the energy sector fits into a world where digitalization is becoming an integral part of society, I understand that you have emphasized the importance of active participation by consumers as well as suppliers.

Takeuchi: There may be some people who have yet to become familiar with the term Utility 3.0. Utility 1.0 refers to how these businesses grew up as legal monopolies supplying ever-increasing demand, and Utility 2.0 refers to the era when demand had plateaued and efficiency became an important consideration. What I feel is needed now is a transition to Utility 3.0 as a new form of social infrastructure. This extends beyond the transformation of the energy industry, instead encompassing reform of all areas of social infrastructure.

When you consider the context of energy, it will continue to be a mix of both large-scale centralized infrastructure and distributed infrastructure such as local supply schemes for a time. In the case of large-scale centralized infrastructure, I believe central government has a high level of responsibility. With distributed infrastructure, on the other hand, private-sector ingenuity plays an important role, with the development of new industries through co-creation among industry and other parts of the private sector. For example, the reason why carbon neutrality has yet to spread to all citizens is because energy is essentially a means to an end and carbon dioxide (CO_2) is a byproduct of activity. It is much like the idea of how waste is generated as a byproduct of people's activities. If, instead of demanding that they shift to activities that do not generate CO_2, consumers are offered products and services that they want to use because they find them attractive, convenient, and trouble-free, it is their choices that will bring about a reduction in CO_2. This, I believe, is the key role of industry. If we are to create such products and services, we need to be thinking about how we can create new added value through combined efforts that go beyond the energy industry to include other industries such as mobility or housing. Digitalization has a key role to play. While Utility 3.0 encompasses a multitude of meanings, this is the sort of world it is seeking to create (see Figure 2).

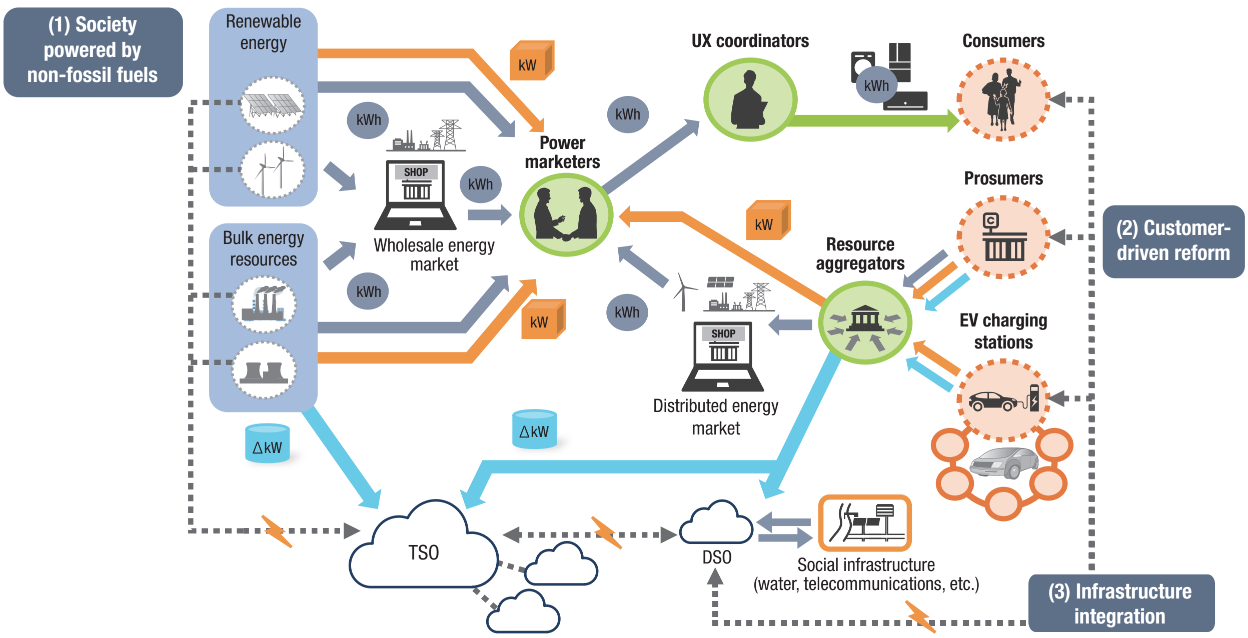
Katsuno: Carbon neutrality and digital technology are two sides of the same coin. Three requirements for the societal changes needed to achieve them are: (1) combining these with economic growth and the enjoyment of new forms of abundance, (2) establishing distributed and circular networks, and (3) productivity improvement and diversity.

For the first of these, while there is no doubt that technological innovation is needed to achieve carbon neutrality, how we go about getting such technologies adopted quickly is crucial. We need to establish them as viable businesses that foster economic growth. Also necessary is to ensure that any increased costs are passed on to the public in an appropriate manner so that they are able to enjoy lives that are safe and secure as well as prosperous. Achieving this requires progress on international standardization and launching initiatives overseas. Without such ambitions, it is unlikely that much progress will be made on carbon neutrality. Another crucial factor is digitalization. It is likely that digitalization will open up physical infrastructure such as energy and telecommunications and societal infrastructure such as education and healthcare to greater scrutiny. Also important is the challenge of how this data can be made available on platforms to facilitate changes in industry and in public and private life, and what new value and services can be delivered from the fusion of the cyber and physical realms. As customers and the companies and other organizations involved in the value chain make great strides, what vision should we be sharing and what approaches should we be adopting as we communicate with them? This is the first requirement.

The second requirement relates to the goal of combining resilience and quality improvement with greater efficiency in the economy and society. A more distributed energy system has a strong affinity with the circular economy in that both are associated with a way of life based on local sourcing that is underpinned by digital technology. It is anticipated that the shift to these will happen in tandem. As each community is different, they can achieve higher

Figure 2 | The World of Utility 3.0

Network unbundling is what differentiates Utility 1.0 and 2.0. Utility 3.0 refers to new societal systems that extend beyond energy. As both large-scale centralized infrastructure and distributed infrastructure continue to coexist, ways are needed to ensure that they are developed and maintain reliably.



Source: Adapted from “Energy Industry in 2050—Game Change to Utility 3.0” (Nihon Keizai Shimbun, Inc.)

UX: user experience TSO: transmission system operator DSO: distribution system operator levels of overall efficiency and performance and improve resilience through a virtuous circle in which they make things easier for themselves by focusing on doing what they are able to do, thereby achieving stability and improved quality. I believe that making this connection is one of the roles of utilities.

The third requirement recognizes that the development and utilization of a wide variety of talent is essential for a social transformation like carbon neutrality. As well as pursuing diversity and new value creation as measures such as electrification and digitalization make the workforce more dynamic, what this involves in practice includes collaboration with educational institutions and engagement with youth to enable a next-generation approach to training in which investment in human resources enables the necessary re-skilling and recurrent education. The goal is a dynamic society in which people feel motivated and invigorated, with these initiatives contributing to the creation of new value. All three of these are implicit in carbon neutrality.

Takeuchi: I expect that quite a few of the societal challenges we need to solve fall under the banner of carbon neutrality. I am also conscious of a large divide between Japan and Western nations in how we express and convey that vision. Looking at the US Inflation Reduction Act or Europe's REPower EU proposal, for example, I think the specific technologies and approaches are much the same, but the way the vision is communicated is ingenious. The Japanese government has identified the need for JPY150 trillion in investment to achieve carbon neutrality. While the roadmap will require adjustments along the way, what is needed to achieve this, I believe, is a clearer vision and a flagbearer who can show the way.

As for the shift to distributed and circular systems, some very difficult hurdles need to be overcome. The large-scale, centralized infrastructure we have had in the past has featured systems that perform extremely well on efficiency and cost.

However, at a time when Japan's market and society are shrinking and it becomes difficult to maintain large-scale network infrastructure, a major goal like carbon neutrality calls for a transition to distributed and circular practices that take the place of infrastructural functions. When you look at it from that perspective, there is a need for flexibility in how we go about doing things, such as using fossil fuels as a mechanism for maintaining stability of supply in emergencies. I believe this is an issue where industry should take the initiative and present its findings to those in government and the bureaucracy responsible for system design.

Yamada: This is an area where I would like to see not only energy businesses, but also manufacturers like Hitachi getting together to play their part. I would like to see us trialing various different practices to satisfy the technical requirements. As we have been saying, it is also true that little headway will be made on the practical deployment of these practices unless we put in place the three prerequisites of business viability, predictability, and a regulatory regime that underpins these. I also believe it is vitally important that we win the understanding of customers and the general public through open dialogue and debate.

IEEJ as a Forum for Japanese Innovation

Yamada: Katsuno-san, you were appointed the 109th President of the Institute of Electrical Engineers of Japan (IEEJ) in May 2022. Can you please tell us a little about this organization?

Katsuno: Since it was established in 1888, the IEEJ has made a major contribution to the progress and deployment of research into electrical technologies in Japan by bringing together academics and practitioners along with government and universities. Use of electric power has expanded continuously over those 135 years. Telecommunications became established about a decade earlier than electricity, and whereas it has progressed from Morse code to radio transmission, long wave and short wave, and ultimately optical communications, 1 kWh of electricity today is exactly the same as 1 kWh back then. As electricity is such a convenient form of energy, capable of providing light, motive force, or heat, it is fascinating how technological progress has largely been centered on generation and transmission to enable its "generation, distribution, and consumption."

Rinzaburo Shida, the main advocate for the establishment of the IEEJ, spoke at the 1888 IEEJ Annual Conference about nine technologies that he predicted would be developed in the future. In a 1967 pamphlet by Goro Inoue, the first-ever president of Chubu Electric Power Co., Inc. who also served as the 50th President of the IEEJ, he wrote about how the fun to be had from predicting the future was a spur for research and development, noting that, flying cars apart, all of Shida's predictions had come to pass. This was what Shida himself had in mind in his advocacy for the IEEJ: the idea that by providing a forum where scientists and engineers with a diverse range of perspectives and specialties could get together, it would help to advance electrical research and see it put to good use.

This is an idea that I believe makes just as much sense today. Now more than ever, scientists and engineers should themselves be imagining what sort of future society will emerge from the introduction of innovative technologies in pursuit of carbon neutrality and then focus their research and development efforts on this vision.

In its Grand New Design announced in July 2022, the IEEJ talks about how, to achieve its vision for a society that is "prosperous, safe, and secure" as well as "sustainable," co-creation that brings the public together with industry, academia, and government can be fostered by providing a forum for exchanging and reconciling facts and opinions and sharing information, one that also features diversity by engaging and partnering with other academic societies in different fields or from overseas. In particular, achieving carbon neutrality will require not only expertise from other branches of engineering, but also that we work closely with the humanities and social sciences. Along with fostering a consensus view on transforming all areas of society, communication with companies, academic institutions, communities, and the public will be vital. In this, the question of how to convey the thinking of scientists and engineers will be crucial.

Yamada: I have great respect for how, for more than 130 years, the institute has built up large amounts of knowledge and expertise about electrical technology while also helping to bring on the people who work in the field. I recently attended the IEEJ Annual Conference or Technical Meetings where I was able to observe the vigorous debates that took place, noticing also that many young students were in attendance along with the experts. It gave me a sense of how, in its role as a forum, the IEEJ serves as a platform where people from different generations and with different points of view can communicate with one another.

Takeuchi: I was at a symposium yesterday where the topic of discussion was "the weaponization of economics." The value of energy security is not something that anyone gives much thought during peacetime. We don't see it as something that we need to invest in. Nor, however, is it something that we can hurriedly put together when things go wrong. Stability of supply is itself a "value" that society needs. While I talked about the importance of fostering public understanding of this value, in this regard the extensive implementation work being undertaken by the IEEJ is of great importance. It is also important that the institute maintains a prominent role as a professional community that is also involved in bringing forth the next generation of talent.

Katsuno: The IEEJ also plays an important role in international standardization. While this includes the establishment of common technical rules, the scope of standardization nowadays also extends to the value chain and business models. Given this situation, along with leveraging the forum provided by the IEEJ for scientists and engineers to work together on fostering Japanese innovation, it is vitally important that individual scientists build their network of contacts by engaging with others working overseas. The IEEJ is taking the initiative to provide opportunities for debate, inviting experts from industry, government, and academia. I believe that routine activities like this are one way in which we can gain a greater role in international standardization.

Yamada: With growth stalled in the domestic market, the standardization of products should also help with reducing their cost. Likewise, international standardization becomes important if the intention is to move into overseas markets. I see hope for the establishment of such a model with the IEEJ serving as a hub. Naturally, I would also like to see Hitachi among those involved.

Katsuno: As Hitachi is a broad-based manufacturer of electrical equipment, with activities extending from exploratory research not dissimilar to that done in academia to the rollout of infrastructure, home appliances, and other such products, I believe it has a very important role to play. With society at a major turning point, companies too need to change.

Value chains are transforming as the value provided by services evolves with advances in digitalization. Mobility provides a classic example. With the introduction of robots and artificial intelligence (AI), it is evolving into mobility-as-a-service (MaaS) where, rather than just transporting people, it is delivering value through services that derive from that role. This in itself gives it certain attributes of community. Hitachi is engaged in a wide variety of businesses. As such, and given the changes happening in the content and layers of value chains, I would like to see this getting you involved in research and development for the public good as you play your part in managing reform across all parts of society. In the process, I look forward to Hitachi promoting international standards and standardization, leading to international competitiveness and economic security.

Yamada: Hardware remains important, and televisions and cars are changing in a way that satisfies the needs of consumers with content and services, just like smartphones. Recently, a person who works for a telecommunications business told me that they want Hitachi to make society like a smartphone. What they meant by this was a world in which everything can be updated in real time, as it is on a smartphone. Hitachi, I believe, should aspire to be an organization that keeps social infrastructure up-to-date and makes it convenient for everyone to use.

Katsuno: The ability to utilize digital technology to deliver diverse services to families and the wider public creates a need for value providers who will address the issue of how to connect these services. A society built on distributed and circular principles is one that has moved on from the mass production and consumption of the past to the production and consumption of a wide variety of products in small and variable quantities. I expect data platforms like Lumada that link different forms of infrastructure together will also have an important part to play.

Takeuchi: Electricity and other utilities have a strong affinity with manufacturers like Hitachi. While considerable faith is placed in utilities as community-facing organizations that those communities cannot do without, it cannot be said that they have always appreciated the details of how the people in those communities live. My experience of working at an electrical utility is that their goal is to supply electric power to buildings. In contrast, you can expect a manufacturer engaged in everything from social infrastructure to home appliances to have delivered value very close to those consumers' lives. As the way people live varies across different communities, there is considerable scope for both parties to work together on figuring out where we can add value. GX is a transformation of all areas of society, and as such it is important to bring as many different partners on board as we can, including startups.

Yamada: I believe that progress on international standardization can be made by first building up a successful track record of open co-creation based mainly in Japan. I wish you all the best in your future work on achieving carbon neutrality. Thank you for your time today.

GLOBAL INNOVATION REPORT 1

Accelerating Energy Transition and Rapid Increase of HVDC

Atsushi Nishioka | Arman Hassanpoor

NordLink, a ±525-kV/1,400-MW and about 600-km HVDC link that connects Norway and Germany

It is becoming more essential to share resources and reserves across different nations and regions to achieve carbon neutrality. The carbon neutrality raises the utilization of more remote renewable energy sources located far from the demand side. This makes high-voltage direct current (HVDC) a key technology towards carbon neutrality transition. It provides needed infrastructure for transmission of renewable energy over long distances. The number of HVDC projects are increasing rapidly all around the world, a trend that will only accelerate. As an HVDC pioneer supplier and market leader, Hitachi Energy is working hard to meet this high demand for HVDC technology. This article is about the latest trends in HVDC market and technology developments.

Introduction

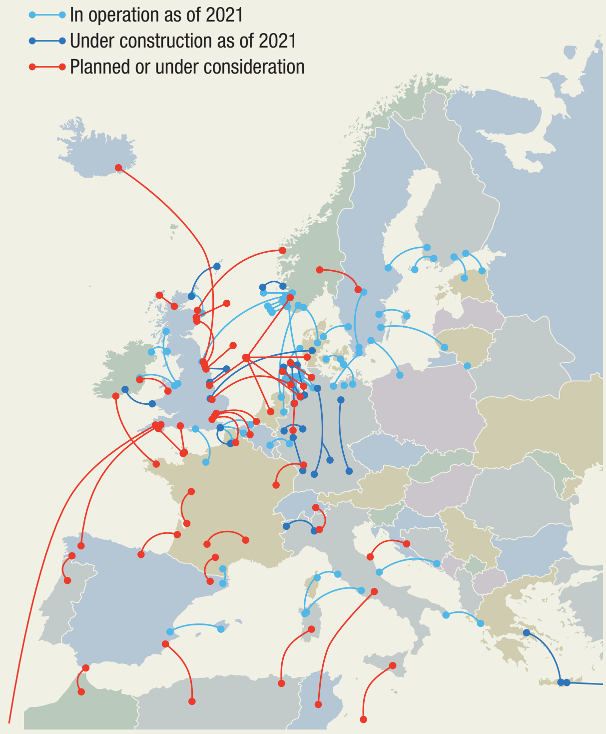
Despite the grid under the European network of transmission system operators (ENTSO-E)*1 coverage has already reached 93 GW of cross-regional and international transmission links, their ten-year network development plan(1), published in April 2022, shows the construction of a further 64 GW of capacity over the coming eight years up to 2030. Figure 1 illustrates the existing, under-construction, and also planned projects in ENTSO-E area. By strengthening

*1 The European Network of Transmission System Operators, which represents 39 electricity transmission system operators from 35 countries.

cross-regional interconnections, ENTSO-E expects to reduce annual carbon emissions by 14 Mt and save five billion euros on generation costs. This will avoid losses of 17 TWh renewable energy curtailment in 2030 by omitting the construction of local ancillary power. In other words, the acceleration in HVDC construction is being driven by its cost and economical benefit. Similar trends can be seen in North America and other regions, with a rapid growth in HVDC links all around the world.

In Japan, there is a considerable debate on ways towards the utilization of renewable energy sources and achieving carbon neutrality by 2050. The long-term policy of wide-area networks (network master plan)(2), published on March 29, 2023, shows more than 10 GW of cross-regional HVDC transmission links will be needed in the future Japanese electrical network. It is anticipated that most of these HVDC links, along with the planned offshore wind connection HVDCs, will be based on voltage source converter (VSC) technology. VSC technology is dominating the HVDC market in recent years. By 2022, a total of 53 VSC HVDC projects had commenced operation all around the world following the first commercial link in Gotland, Sweden by 1999. As of December 2022, this equated to a total capacity of about 44 GW. With numerous projects planned for 2023 and beyond, this cumulative capacity is expected to reach 123 GW by 2028. This trend is shown in Figure 2*2.

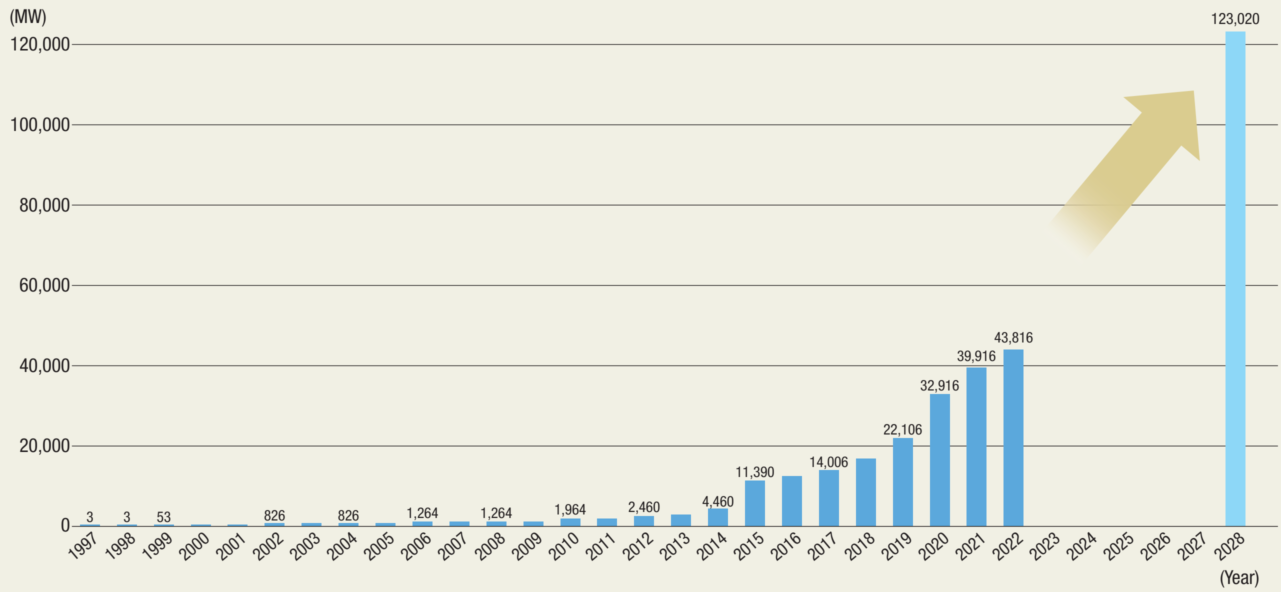
Figure 1 | **HVDC Projects in Europe (ENTSO-E Area)**



HVDC: high-voltage direct current

*2 As of 2022, based on research by Hitachi HVDC Technologies, Ltd.

Figure 2 | **Cumulative Installed Global Capacity and Future Projections for VSC HVDC**



Contribution of VSC HVDC to Existing AC Grids

Although the recent rapid boost in VSC HVDC technology is primarily a consequence of the need for long cable power transmission, another important factor is the contribution of VSC HVDC technology to stabilization of existing alternating current (AC) grids. AC grids are subjected to various forms of instabilities, including voltage instability, frequency instability, power oscillations, and transient instability. Accordingly, the overall grid should be equipped with a variety of countermeasures to either prevent or suppress these instabilities quickly when they occur. However, many of the sites, suitable for large renewable installations, are located where grid infrastructure is weak (low short-circuit capacity), making them prone to such instabilities. It signifies that additional grid stabilization measures will be needed if more renewable capacity is planned to be connected at that site.

The benefits of VSC HVDC technology are listed in following subsections.

(1) Use of VSC HVDC to maintain voltage stability

When VSC HVDC is installed in a region where the grid is weak and subjected to voltage fluctuations, it not only can efficiently transmit the renewably generated power, but also helps stabilizing the voltage on the local grid. Figure 3 shows actual voltage waveforms from a grid in which HVDC is used to stabilize the AC-side voltage. This explains how the reactive power control capabilities of HVDC suppresses the fluctuation in voltage on the connected AC grid.

(2) HVDC in synchronous grids (DC links in AC grids)

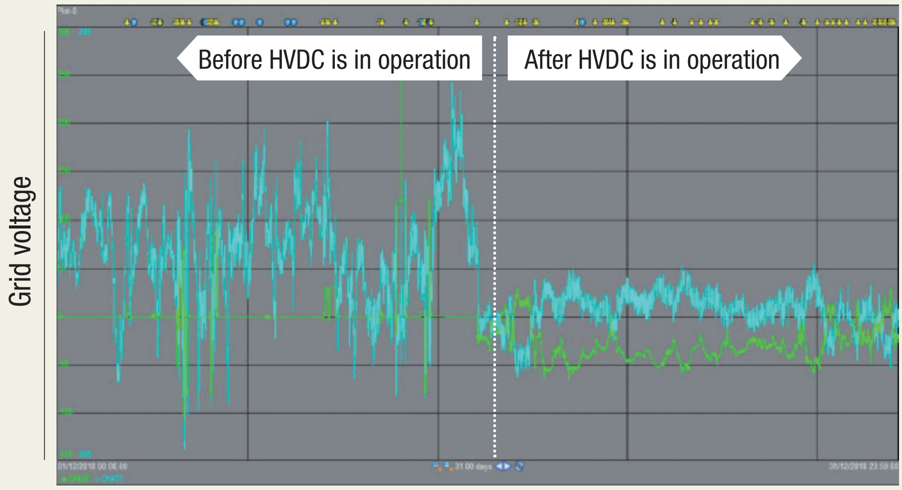
Historically, HVDC was commonly used to interconnect asynchronous grids. However, there are new applications for HVDC in which HVDC links are installed within a synchronous grid, operating in parallel with the existing AC grid. This will improve both efficiency and stability of the connected AC grid.

For example, in the grid shown in Figure 4, when an existing AC grid is subjected to operating under some constraints due to voltage stability, VSC HVDC can mitigate these constraints by controlling reactive power at both ends of the link. Moreover, since HVDC can quickly control active power accurately, it can be used as a damping controller and suppress phenomena on the existing AC grid such as long-period oscillations or transient power swings.

(3) Use of VSC HVDC for transient stability

VSC HVDC can also help stabilize existing AC grids with respect to transients. HVDC links enable operating practices that improve different aspects of transient stabilities in connected AC grids. For example,

Figure 3 | **Example of Grid Voltage Stabilization Using HVDC (Scotland, UK)**

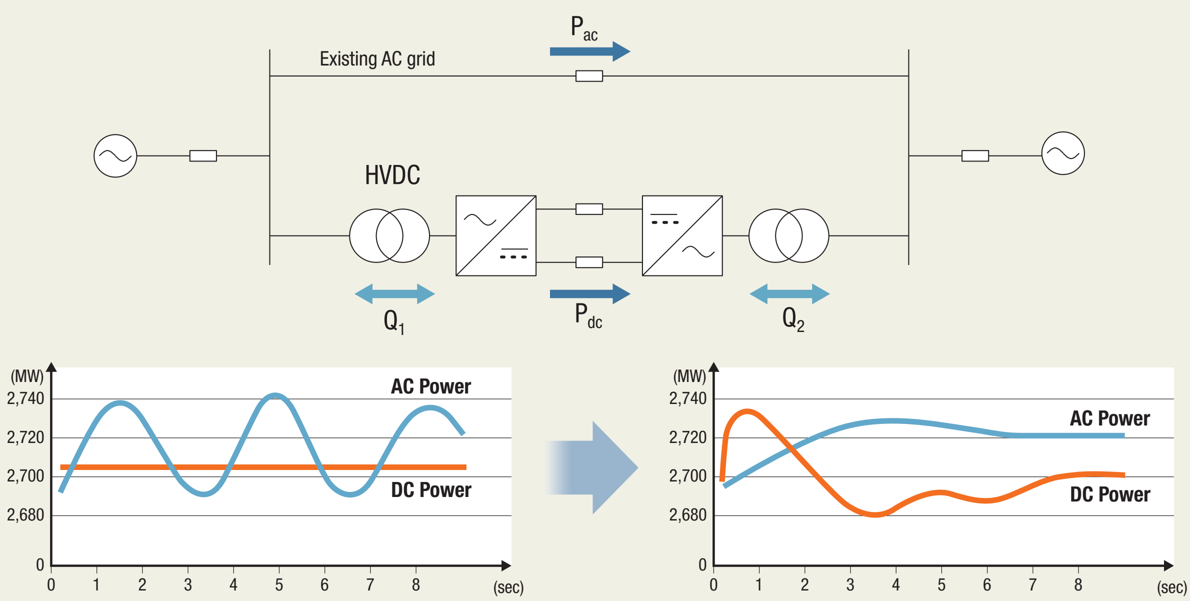


HVDC can supply reactive current to the grid during a fault to minimize voltage drop, and HVDC's fast power control prevents voltage collapse and suppresses changes in frequency and power fluctuations after a fault is cleared. Figure 5 shows an example of the improvement in transient stability achieved in Newfoundland, Canada.

(4) Support for lack of grid inertia

It is anticipated that connecting large amounts of renewable energy to a grid will make it more vulnerable to frequency fluctuations due to a reduction in the number of grid-connected synchronous machines that provide inertia. For instance, if a large generator steps out, the disruption to the balance of supply and demand causes a declining frequency. The less inertia is available on the grid, the greater the resulting rate of change of frequency (RoCoF) and peak frequency drop (nadir). Moreover, if the nadir exceeds a certain value (if the frequency drops by more than a certain amount), other generators are unable to maintain operational stability. It will increase the risk for cascading failures that can result in a major power outage (blackout)[(3), (4)].

Figure 4 | **Installation of VSC HVDC in Parallel with Existing AC Grid**



DC: direct current AC: alternating current

Figure 5 | **Transient Stability Improvement by Use of HVDC in Newfoundland, Canada**

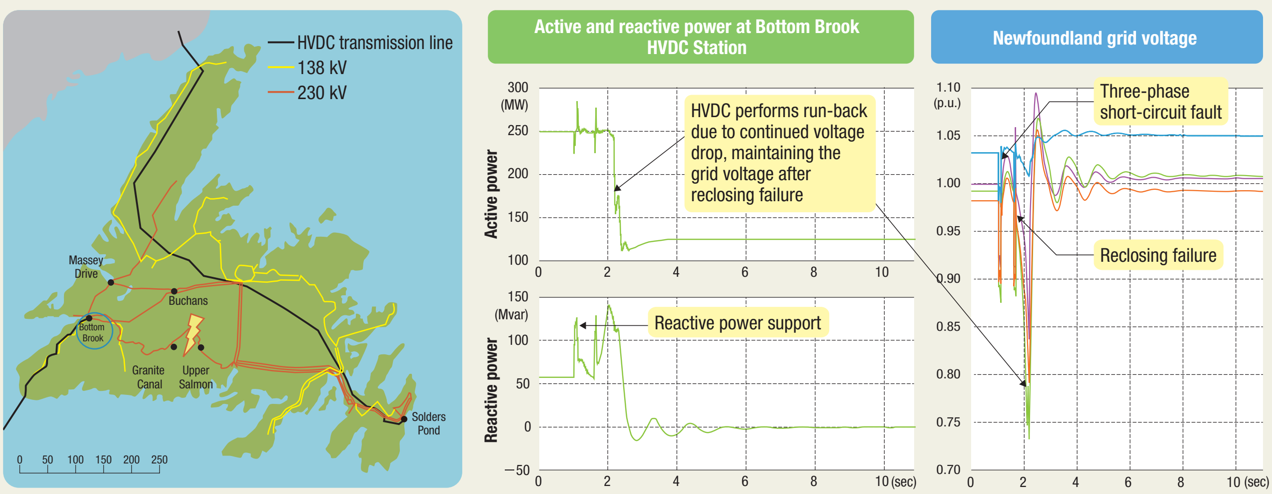
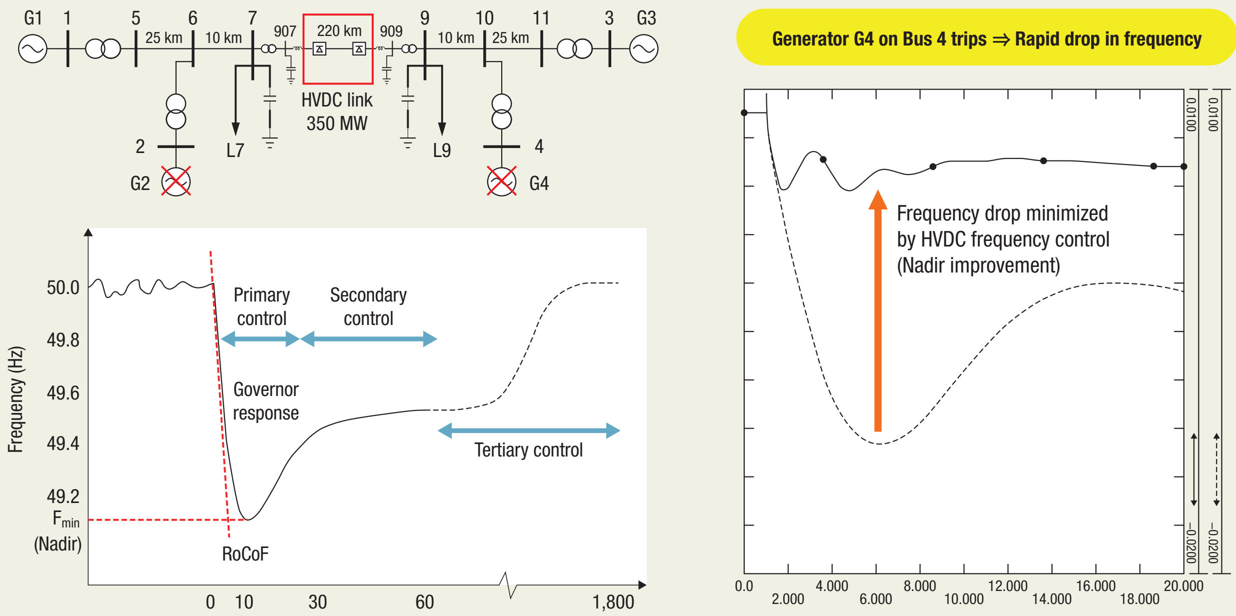
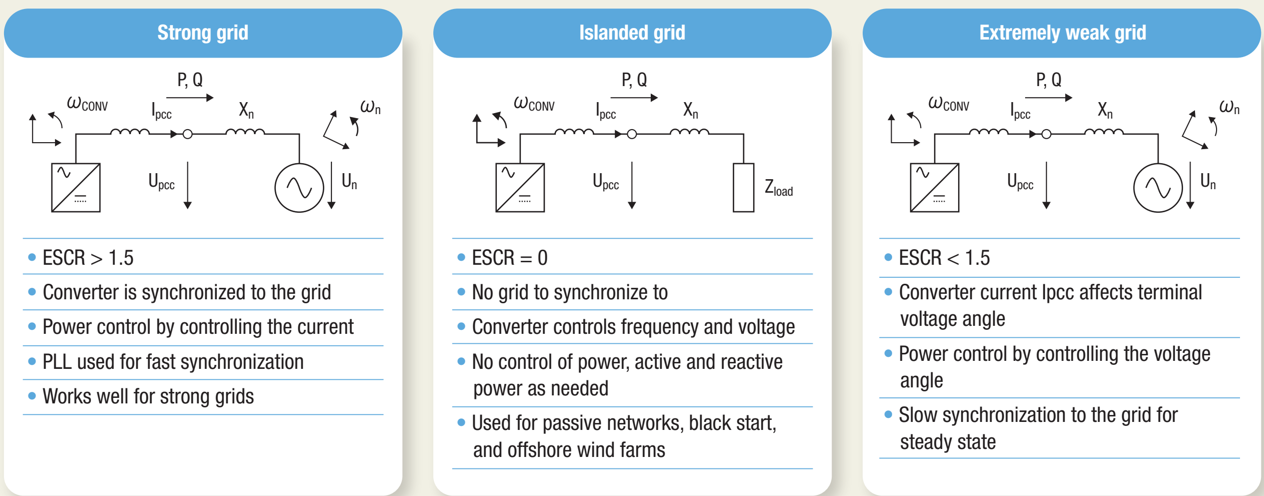


Figure 6 | **Simulation Using Kundur 2-Area Model**



RoCoF: rate of change of frequency

Figure 7 | **Use in Different Types of Power System**



ESCR: effective short-circuit ratio PLL: phase-locked loop

While various countermeasures such as synchronous condensers, etc. have been considered for addressing this problem of reduced inertial energy (Ws), HVDC's emergency power control, that controls active power within a second can be another potential solution for supporting grids. While HVDC does not itself possess inertia, it can minimize frequency drop on a grid suffering from a power shortfall by rapidly augmenting it with energy from the other grid. Figure 6 shows a simulation result of how HVDC's fast power control improves the nadir frequency.

(5) Augmenting extremely weak grids with grid-forming control

VSC HVDC can operate on grids with low short-circuit capacity, which was difficult for conventional line-commutated converter (LCC) HVDC. It can also augment the stability of such weak grids. Figure 7 depicts different control strategies in different types of grids.

If a grid is sufficiently strong, HVDC uses vector current control to control active and reactive power. This means it acts as a current source in the grid.

This is what is known as grid-following (GFL) control (left column in Figure 7). On a grid with low short-circuit capacity (effective short-circuit ratio < 1.5), on the other hand, converter output current has a large effect on the voltage phase at the point of common coupling (PCC), making HVDC operation less stable if GFL control is used. Accordingly, grid-forming (GFM) control is used instead (right column in Figure 7).

With GFM control, the converter acts as a voltage source and, in place of conventional vector current control, the amplitude and phase of the converter output voltage are controlled directly to maintain a stable voltage phase at the PCC. The synchronizing power is adjusted by using frequency droop to control the phase of the converter output voltage.

As this control strategy allows HVDC to maintain stable operation on extremely weak grids, it has already been widely adopted as a solution where the local grid is weak, as is often the case at renewable energy generation sites.

Conclusions

VSC HVDC plays an important role in expanding the use of renewable energy all around the world while it also helps to improve the stability of existing AC grids. It represents an effective and economic solution for Japan as it seeks to achieve carbon neutrality, providing benefits to a variety of different power systems while also getting renewable energy to the places where it is needed.

Hitachi Energy has been involved in many VSC HVDC projects all around the world and developed this technology according to the market technical demand. The developed HVDC technologies can cover the voltage and capacity specifications required in Japanese grids. The knowledge gained from worldwide installed based Hitachi Energy HVDCs can support HVDC project planning, execution, and commissioning in Japan and contribute to strengthening the domestic electricity transmission network by supplying already well-proved technologies globally.

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GLOBAL INNOVATION REPORT 2

Digitalization Trends and Policies for Achieving 24/7 Carbon-free Energy

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Efrain Tamayo | Masaaki Ito | Hugo Stappers

A wide range of policies are being implemented globally to achieve a carbon neutral society. Among these, a new trend is to expand initiatives for achieving 24/7 carbon-free energy, which is the continuous utilization of renewable energy sources that are subject to generation fluctuations depending on the weather. It has become widely accepted that in order to achieve true carbon neutrality, management of renewable energy generation and consumption at a highly granular hourly level is required. Hitachi is participating in projects such as the EnergyTag initiative for the standardization of 24/7 carbon-free energy, and is collaborating with Hitachi Energy Ltd., to develop specific solutions that utilize digital technologies. This article describes Hitachi's efforts to contribute to the decarbonization of society by implementing a digital transformation cycle for achieving carbon neutrality based on a data-driven approach using highly granular data.

Global Trends for Achieving 24/7 Carbon-free Energy

Governments worldwide are implementing various policies such as utilizing energy attribute certificates (EACs) and power purchase agreements (PPAs) to achieve a carbon neutral society. However, full decarbonization will require even greater deployment and expansion of renewable energy, creating new challenges in related markets and technology development fields. On the other hand, because the deployment of renewable energy is not the ultimate target, to achieve carbon-free energy (CFE) additional actions will be required.

The EAC trading system is not directly linked to timing of electric power generation and the physical conditions of the electric power system, resulting in temporal and spatial discrepancies. In order to bridge this gap, it is necessary to certify that the renewable energy procured under agreements based on hourly units is the same as the electric power supplied to the demand side. Since renewable energy is affected by weather and other factors, the deployment of such energy is subject to both time and location constraints when generating electricity. Therefore, there is a need to encourage the new deployment of renewable energy that meets these requirements, while continuously and effectively integrating the renewable energy into existing power systems and trading systems. 24/7 CFE* has been conceptualized to achieve this. Under 24/7 CFE, matching CFE generation and consumption at a highly granular temporal level of an hour or less is positioned as a critical requirement.

The EnergyTag[1] initiative is based in the UK and was established to promote a deeper understanding of 24/7 CFE. In March 2022, the EnergyTag initiative published standards and guidelines for Granular Certificates (GCs), which are issued, traded, and written off similarly to EACs (see Figure 1). Hitachi joined in the standardization process and is one of more than 100 supporter organizations of EnergyTag. In the data center field, the implementation of GCs has already started spontaneously, and studies are continuing for application in other fields such as green hydrogen, methane, and ammonia. The international standardization organization for

* The concept of supplying electric power with zero carbon emissions to the power supply network and using such power in real time, 24-hours a day, 7-days a week (continuously).

Figure 1 | Trends Related to 24/7 CFE by Region

Region	24/7 CFE-related trends by region
Europe	• EnergyTag initiative published standards and guidelines for 24/7 CFE • European Commission encouraged use of 24/7 CFE in manufacturing fields such as green hydrogen (from 2030)
North America	• US government published a policy to procure more than 50% of electric power used by the government as 24/7 CFE by 2030
Rest of the world	• I-REC is promoting studies for standardization of hourly certificates • 24/7 CFE demonstration projects promoted in Australia, Taiwan, Singapore, Chile, and others

CFE: carbon-free energy

renewable energy certificates (I-REC)[2] is expanding its scope to fields such as decarbonization and hydrogen, in addition to certification by hourly unit. In the future, the deployment of 24/7 CFE is expected to be an important step toward the disclosure of greenhouse gas (GHG) emission amounts, which is required for strict carbon accounting.

Importance of Disclosing GHG Emission Information

A growing number of companies worldwide are disclosing information about their decarbonization activities in conformance with the Task Force on Climate-related Financial Disclosures (TCFD)[3]. According to information published by TCFD on September 22, 2022, a total of 3,819 companies and organizations around the world had agreed to disclose information of which, 1,062 companies and organizations are in Japan.

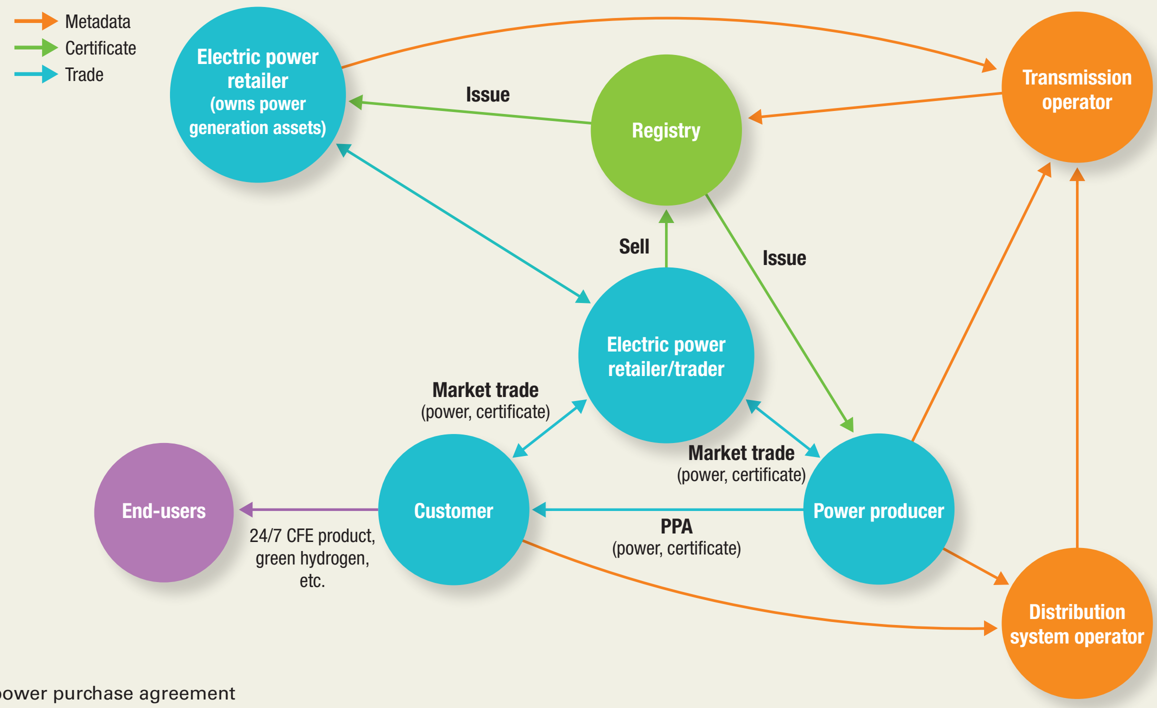
TCFD disclosures are composed of four categories, which are Governance, Strategy, Risk Management, and Metrics and Targets. The Metrics and Targets category requires the calculation and reporting of the amount of GHG emissions according to internationally recognized GHG protocols. The GHG protocols are divided into three categories, which are Scope 1 (direct emissions), Scope 2 (indirect emissions), and Scope 3 (other emissions), depending on how the gas is emitted and who emits the gas. As the deployment of renewable energy continues to grow, in addition to asset management and energy management, tasks for understanding, calculating, and reporting GHG emissions will become even more important in the future at companies and other organizations that report emissions. In Japan, the Tokyo Stock Exchange (TSE) revised its Corporate Governance Code in June 2021 to make it compulsory for the 1,839 companies listed on the Prime Market to disclose information according to the TCFD framework.

Furthermore, under Scope 3, reporting is not confined to the individual company, but is required for the entire supply chain, which reveals to the customer the total carbon amount related to the delivered product. Already, there are cases globally of customers demanding companies to certify that the electric power related to the delivered product originates in renewable energy on an hourly basis. Such calls for proof that the energy itself is carbon-free are expected to spread globally in the future.

Innovative Energy Management Based on Digital Technology Utilization

Hitachi is strengthening its digital solutions and utilizing a wide range of electric power system solutions. In the future, Hitachi will provide even more GC-related solutions to contribute in a comprehensive manner to customer decarbonization. Hitachi will provide highly trustworthy certification, risk reductions,

Figure 2 | Configuration of Ecosystem for Utilizing Granular Certificates



PPA: power purchase agreement

and optimal procurement for electric power and GCs to form an ecosystem that takes into account activities covering various stakeholders and end-to-end (E2E) processes (see Figure 2). Hitachi's aim is to coordinate the behavior of various related stakeholders to ensure commitment to and cooperation with the local community.

Currently, EACs such as the RECs in the USA and the guarantee of origin (GO) certificates in Europe are purchased either in the form of electric power via PPAs, or are purchased separately via a method that is not linked to the electric power after procuring power from a power trading market. In contrast, Hitachi's innovative energy management utilizing digital technology matches consumers and suppliers in advance to procure the power and the linked GCs at the same time, which enables trading on a private market managed by the electric power retailer. If linked GCs cannot be acquired according to customer requests, GCs not linked to the power can also be provided in a supplementary manner. In addition to operational planning for power supply and demand, past results and forecast data are used to optimize supply and demand. This enables pre-matched trading that uses the flexibility of both supply and demand to enable the maximum utilization of unused renewable energy. Renewable energy trades between supply and demand are matched at a highly granular level that enables energy traceability to be provided for electric power that includes both renewable energy and other energy sources.

Energy storage plays an important role in providing flexibility over a wide range of renewable energy uses. As such, Hitachi is developing GC management technologies for storage battery charge and discharge power to make it possible to provide consumers of the charged and discharged renewable energy with GCs. Since electric power loss occurs when the electricity of storage batteries is charged or discharged, this can be taken into account to implement highly reliable GC management. A future goal of Hitachi is to achieve 24/7 CFE by optimizing the entire system including power consumption, generation, and equipment such as storage batteries in the power grid.

As a part of disclosing GHG emissions information, GCs will be used when reporting about decarbonization throughout the entire supply chain for products manufactured using 24/7 CFE, which will enable final certification of the products as being manufactured through fully sustainable methods. Such proof is essential for environmentally conscious manufacturers, service providers, end users, and other customers. As a result, the use of GCs will increase the value of environmentally friendly claims by communicating to the outside world that the power utilized in manufacturing processes is 24/7 CFE.

Digital Transformation Cycle for Phased Implementation of Carbon Neutrality

For customers and other energy consumers, achieving carbon neutrality by 2050 is an extremely tough challenge. It is important to accurately understand current conditions to create and then gradually implement a medium-to-long term strategy. However, many companies are likely to be unsure of how to devise policies that will meet such ambitious plans and targets.

Activities for achieving carbon neutral energy are divided into the four categories of "Strategy creation and update," "Work design and system requirements," "Highly granular operation management," and "Report and review" (see Figure 3). Firstly, "Strategy creation and update" describes a roadmap for the actions to take by 2050. Then, "Work design and system requirements" designs specific implementation measures for short-term actions to take from the roadmap. This requires not only plans to increase renewable energy, but also operational considerations, such as the related equipment and work. Next, in "Highly

Figure 3 | **Digital Transformation Cycle for Achieving Carbon Neutrality**

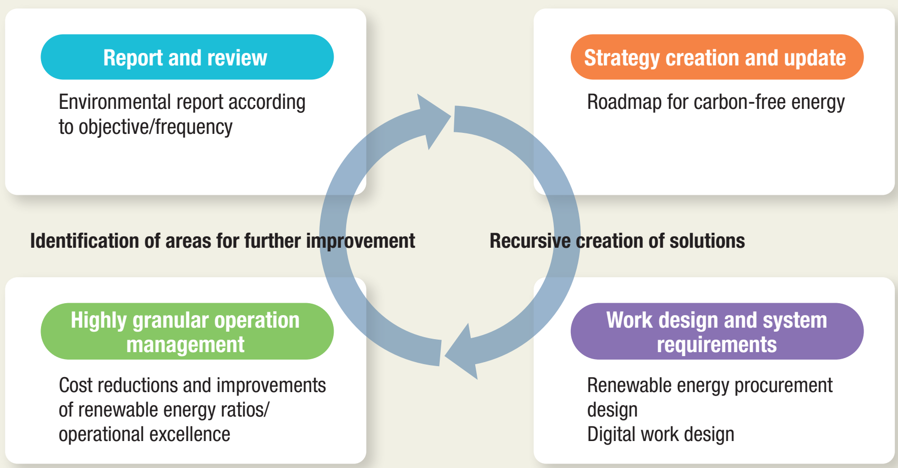
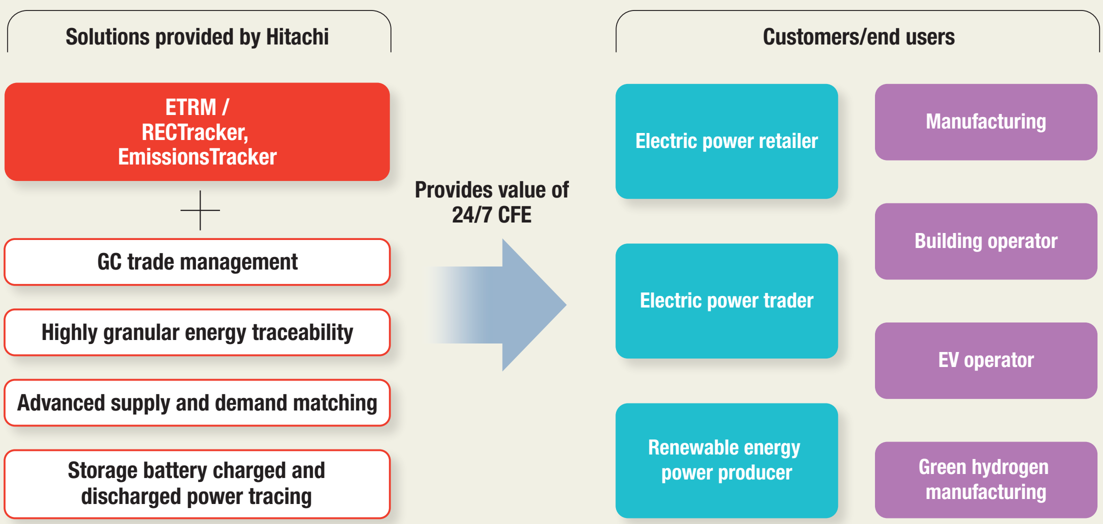


Figure 4 | **Solutions Provided by Hitachi for Customer and End User 24/7 CFE Utilization**



ETRM: Energy Trading and Risk Management GC: Granular Certificate EV: electric vehicle granular operation management," the carbon neutral policies are implemented and operations are performed continuously by increasing the renewable energy ratio steadily while also keeping an overall balance with cost effectiveness and operational excellence. Finally, in the "Report and review" phase, the results of improvements are identified and compared to the roadmap, and a report suitable for the objectives is generated. This report will serve as the basis for updating the roadmap for the second cycle. These four activities are not performed just once. Rather, as far as possible, they are implemented continuously and regularly while checking the most recent conditions of the business environment. This is important in order to steadily achieve carbon neutrality, a goal that is difficult to meet in the short term.

Policies for Providing Global Solutions

In 2020, Hitachi acquired the Power Grids business of ABB Ltd. (now known as Hitachi Energy Ltd.). Then, Hitachi Energy acquired the US company Pioneer Solutions LLC, enabling it to provide Energy Trading and Risk Management (ETRM)/RECTracker, and Emissions Tracker products(4) in the commodity/energy trading (including EACs) and risk management solution markets. The global team of business units, sales units, and research and development works together to provide comprehensive solutions that accelerate the 24/7 CFE utilization of customers and end users (see Figure 4).

Furthermore, to optimize power trading at a granularity of one hour or less, while comprehensively taking into account the environmental value, costs, and other various risks involved in power trading, Hitachi is developing highly granular energy traceability that enables GC trading management, advanced supply and demand matching based on power generation and demand forecasting, and GC management technologies for power charging and discharging of storage batteries. The comprehensive utilization of these policies will enable the continuous implementation of the digital transformation cycle for achieving carbon neutrality, resulting in the efficient use of renewable energy with no waste and helping to increase environmental value for customers.

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Digitalization Trends for Ensuring Power System Resilience

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Darren Jones | Marek Florkowski, Ph.D.

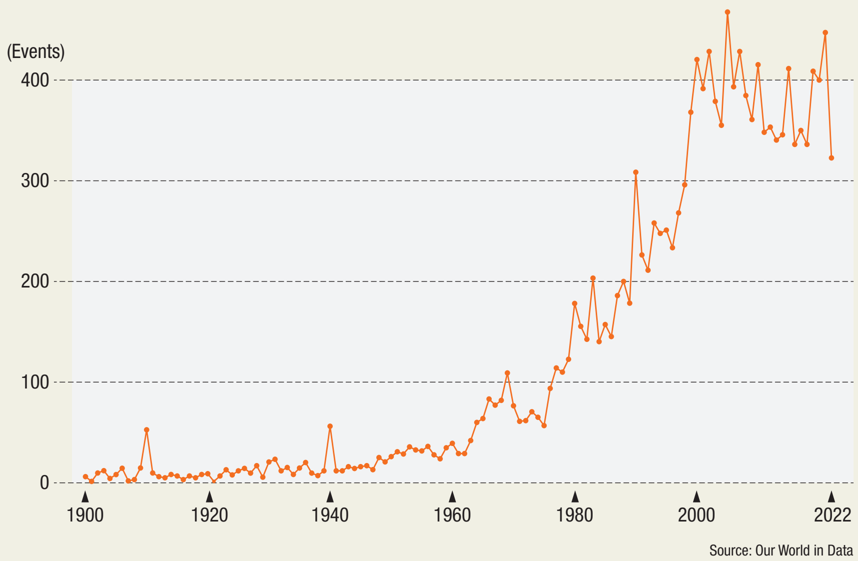
Energy utilities provide the foundation for all the activities of society. Strengthening their resilience to ensure they can continuously provide services is a critical challenge for these companies. Power companies use an enormous amount of equipment for a very long time, leading to the risk of degradation. Also, because most equipment is installed outdoors, devices are exposed to risks from the natural environment. Furthermore, now that distributed and networked control systems have become widely used, they also face external threats, such as cyberattacks. Power companies must understand these various risks and take appropriate countermeasures. It is important to have resilience so that if one of these risks actually results in an incident, the issue is quickly detected, and its impact is mitigated. This article describes digitalization trends for strengthening resilience by understanding risks and mitigating their impact, and the development of field service management solutions.

Introduction

The movement toward a carbon-neutral society has gained momentum in recent years, triggering further electrification throughout the economy, and placing greater responsibility on electric power systems, which are core systems of social infrastructure. However, electric power and other infrastructure systems face growing threats and uncertainties, leading to demand for strengthened resilience. Pandemics, natural disasters, geopolitical risks, and cyberattacks have already turned these threats and uncertainties into reality. Infrastructure systems such as electric power, gas, and telecommunications affect each other, and it is difficult to eliminate uncertainties if each operator works independently. Even though

Figure 1 | Increased Frequency of Natural Disasters

This graph shows the trend for the number of natural disaster events reported globally from 1900 to 2022. These events include droughts, floods, abnormal weather, extreme temperatures, landslides, wildfires, volcanic activity, and earthquakes.



uncertainties cannot be completely eliminated, it is important to have a system that can respond if sudden, unexpected, and uncertain events occur.

The reality is that incidents involving cyberattacks on infrastructure systems are increasing. Natural disasters are also becoming more frequent (see Figure 1)[1]. In response, power companies and governments in North America are conducting evaluations and countermeasures to ensure the safety and resilience of power transmission networks, including consideration of the surrounding environment[2, 3]. The UK government and power companies are seeking to introduce stress tests for resilience, and holistic (comprehensive) metrics for evaluating overall resilience countermeasures[4].

In this context, there is demand for power companies to reveal their specific policies for strengthening the resilience of their power systems. This article describes trends in strengthening power system resilience and the actions taken by Hitachi.

Trends in Strengthening Resilience

Currently, efforts to strengthen resilience are continuing. The focus is on strengthening resilience not only to counter threats such as cyberattacks and abnormal weather, but also as a key concept for power systems that aim to become net zero and carbon neutral.

Strengthening resilience requires improved threat resistance and recovery capabilities. Resistance capabilities have been improved previously by enhancing equipment robustness and redundancy. To improve recovery capabilities, a holistic approach is required for countermeasures that span entire organizations, networks, and equipment (see Figure 2).

This has posed a new challenge: the need to establish a method for evaluating and proving resilience in a demonstrable way. A concept is required that goes beyond the normal boundaries of risk management. Normal risk management is based on the concept of accepting risks by evaluating the probability of occurrence and scale of impact. However, high-impact, low-probability (HILP) events may occur that result in sudden, unexpected, uncertain, and serious incidents. There is a limit to resistance capabilities against the impact of such incidents through equipment robustness and redundancy, placing pressure on recovery capabilities for returning systems to their original status. One policy idea is to impose stress tests based on a series of key performance

Figure 2 | Resistance Capabilities and Recovery Capabilities

Resistance capabilities are the capacity to minimize the scale of damage caused by threats such as natural disasters and cyberattacks. Recovery capabilities are the capacity to quickly restore damaged systems and equipment to their normal levels.

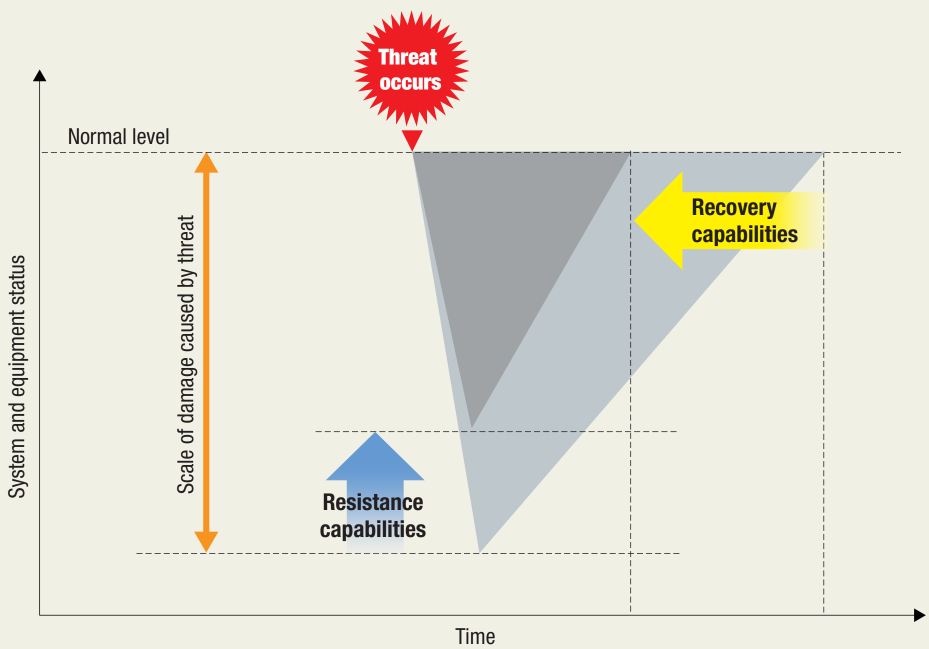
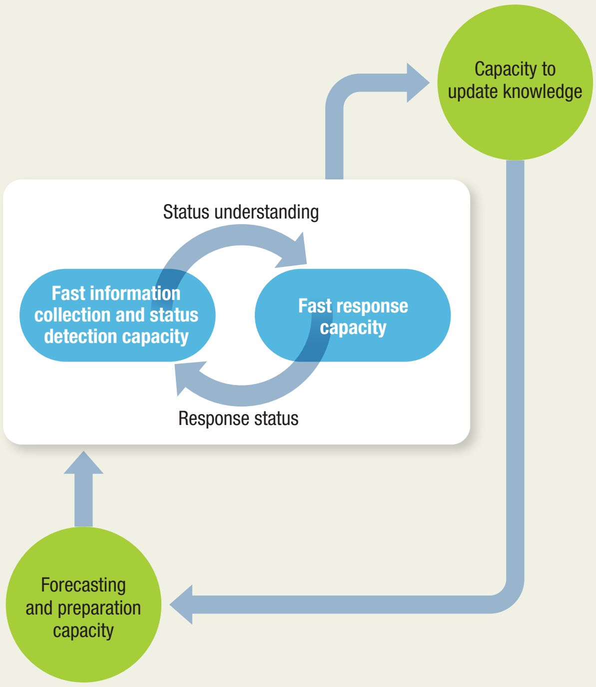


Figure 3 | **Concept of Recovery Capabilities and Capacity for Improving Recovery Capabilities**

Recovery capabilities are composed of reserve capacity to prepare for sudden and uncertain threats, stockpile forecasting and preparation capacity, and the capacity to quickly detect the details and take action should a threat occur. These capacities are strengthened via a capacity improvement cycle based on updating knowledge after the fact.



indicators (KPIs) that integrate resistance capabilities and recovery capabilities[5]. Wider discussion is required for defining the technologies and solutions that can provide recovery capabilities, and then these need to be refined further.

In particular, the following capacities are required to strengthen recovery capabilities:

(1) Forecasting and preparation capacity

(2) Capacity for incident detection based on fast information collection

(3) Fast response capacity

(4) Capacity to improve the first three capacities by updating knowledge through after-the-fact reviews of incidents[6] (see Figure 3).

As described above, evaluations of resilience policies should be designed from the perspective of resistance capabilities and recovery capabilities, taking an approach that covers entire organizations, networks, and equipment.

Policies for Solving Resilience Issues

Hitachi is working to improve the resilience of power systems. As previously described, to strengthen resilience, it is important not only to improve resistance capabilities, but also recovery capabilities. It is making efforts not only to increase the robustness and redundancy of equipment and systems to improve resistance capabilities, but also to strengthen organizational capacity to improve recovery capabilities when recovering from a sudden, unexpected, and uncertain event. This organizational capacity related to recovery capabilities can be strengthened through the digital transformation (DX) of work processes.

The ability to respond to sudden, unexpected, and uncertain incidents can be improved through step-by-step leveling up of capacities; starting with forecasting and preparation, progressing to fast information collection, then the organizational capacity for a fast response, and finally the ability to improve all these capacities by updating knowledge. Hitachi views this model as an opportunity to improve resilience capacities from the perspective of the resilience proficiency model shown in Figure 4.

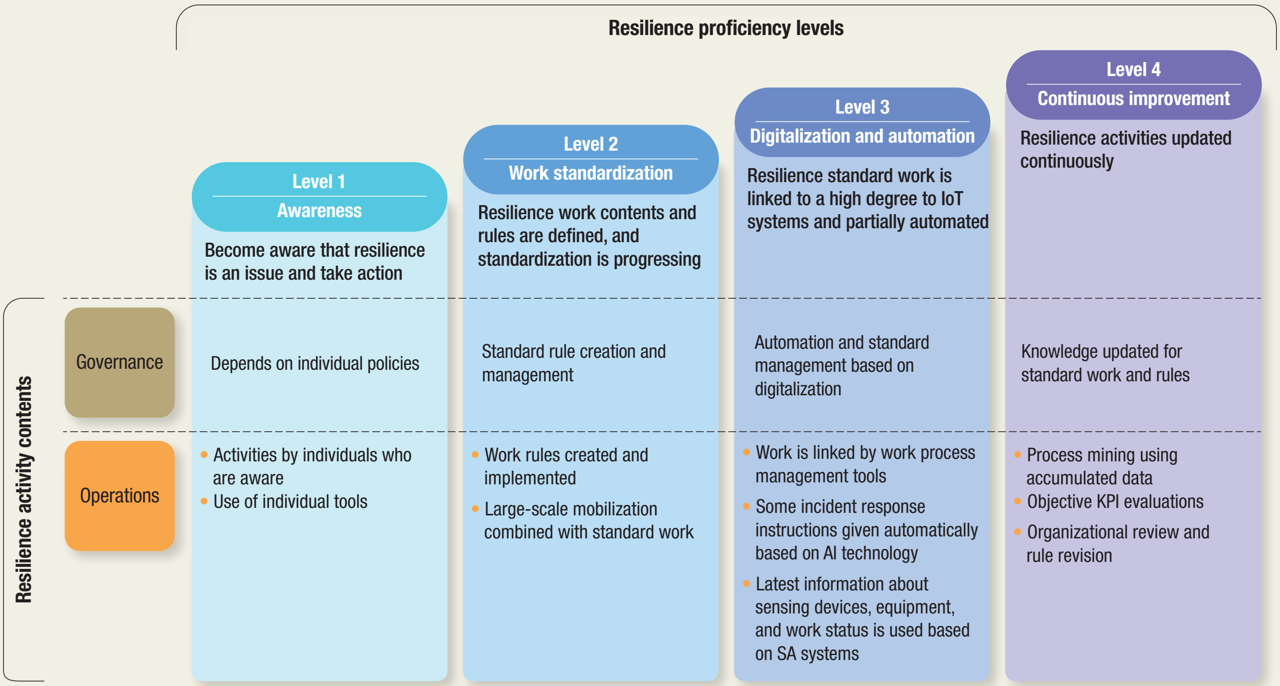
The important concepts in this resilience proficiency model are awareness, work standardization, digitalization and automation, and updating and accumulating knowledge through continuous improvement.

Level 1 is the phase where an individual becomes aware that resilience is an issue, and takes action to respond to sudden, unexpected, and uncertain incidents. In this phase, resilience activities are not standardized across the organization and depend on the initiative of individuals. Individual actions and the use of individual tools correspond to this level.

Level 2 is the phase where the organization defines the work details and rules of resilience and promotes standardization. Organizational knowledge is defined and stored for use by succeeding personnel in the form of rules. Work standardization enables standard tasks to be combined and more manpower to be dedicated to network and equipment resilience. The management of work processes using digital systems corresponds to this level.

Figure 4 | **Hitachi's Concept of a Resilience Proficiency Model**

Resilience is strengthened through the phases of "Level 1: Awareness," "Level 2: Work standardization," and "Level 3: Proficiency in digitalization and automation." Furthermore, "Level 4: Continuous improvement" strengthens resilience by continuously performing improvements based on updating knowledge via updates to the standard work and rules of resilience activities.



IoT: Internet of Things AI: artificial intelligence SA: situation awareness KPI: key performance indicator

Level 3 is the phase where standard resilience work is linked to a high degree to Internet of Things (IoT) systems and some activities are automated. The automation of incident responses based on artificial intelligence (AI) technology and the visualization of worksites by integrating sensing devices, equipment, and work processes correspond to this level.

Level 4 is the phase where resilience activities are updated continuously. This is performed as necessary according to changes in the operational environment, such as weather fluctuations or changes in cyberspace. This level encompasses process mining using accumulated data, and rule management that includes revising rules based on objective KPI evaluations, and adapting inherited knowledge to changes, leading to further refinement of rules.

Hitachi has proposed a digitalization framework with the objective of improving recovery capabilities, which will support rule management for resilience activities and automation (see Figure 5). The key points of this framework are shown below.

(1) Digitalization of information collection

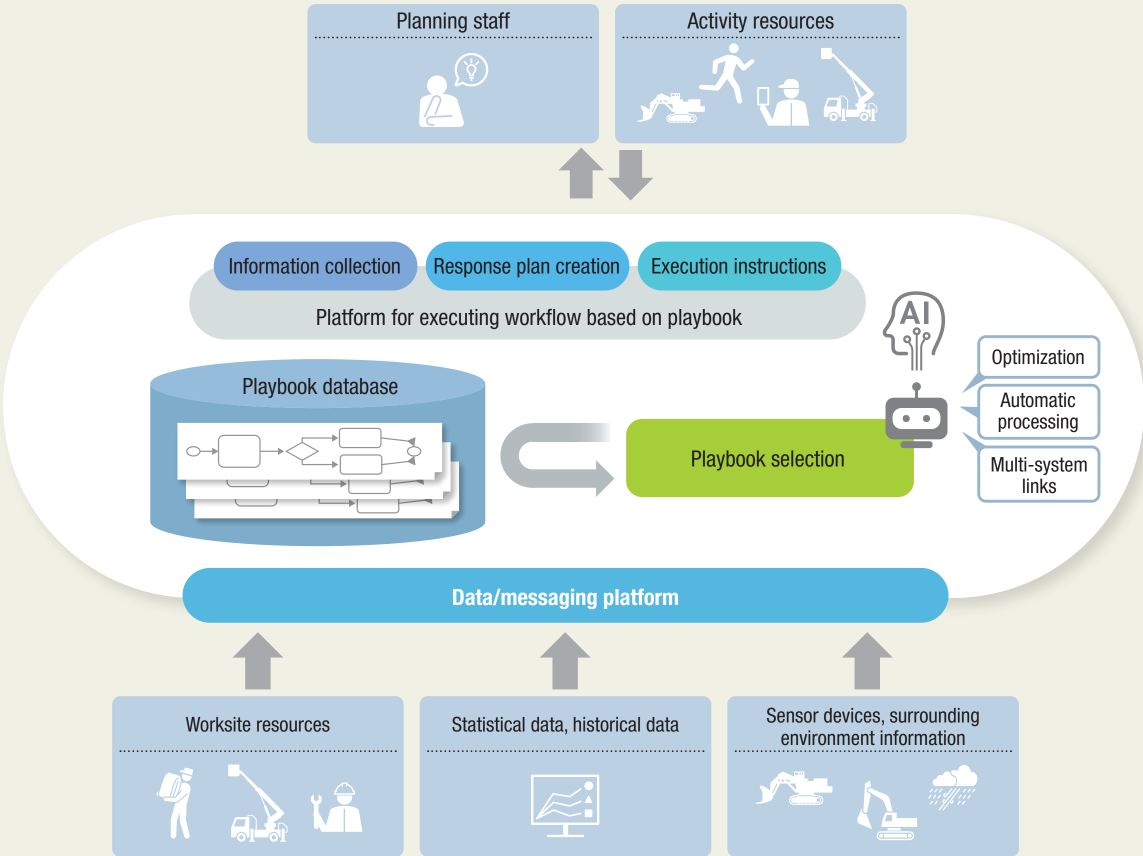
The digitalization of information collection enables faster and more efficient patrol inspections. Also, in the USA, tests have been conducted of patrol by aircraft using digital technology to detect incidents as soon as possible by identifying radio wave and infrared radiation from phenomena (arc discharge, temperatures rises) that cause wildfires. In the future, this is expected to raise the quality of work to a level higher than is possible with visual patrols by humans.

(2) Documentation of rules in a digital playbook that describes how to respond to incidents

Digitally recording the response to incidents and documenting the rules of resilience activities that have been standardized as organization activities are key steps to increase resilience abilities from Level 1 to Level 2 in the resilience proficiency model. Hitachi has also proposed a playbook, which is a definition file that digitally describes the series of processes for

Figure 5 | **Digitalization Framework for Resilience Activities**

Hitachi has proposed a framework to support the digitalization of information collection, the digitalization of incident response rules, and the optimization of responses using AI. The playbook digitally records the responses to incidents and digitalizes resilience activity rules that have been standardized as organization activities. These are accumulated as organizational knowledge.



collecting information, creating a response plan, and executing instructions. This playbook is a key step in raising resilience capabilities to Level 3, where activities start to be automated. When considering a response to sudden, unexpected, and uncertain incidents, a playbook that is not dependent on existing systems should allow all elements to be different, such as the simulators, data storage locations, and external systems storing the data related to each incident. This playbook stores organizational knowledge.

(3) Optimization of responses and automatic creation of schedules using AI

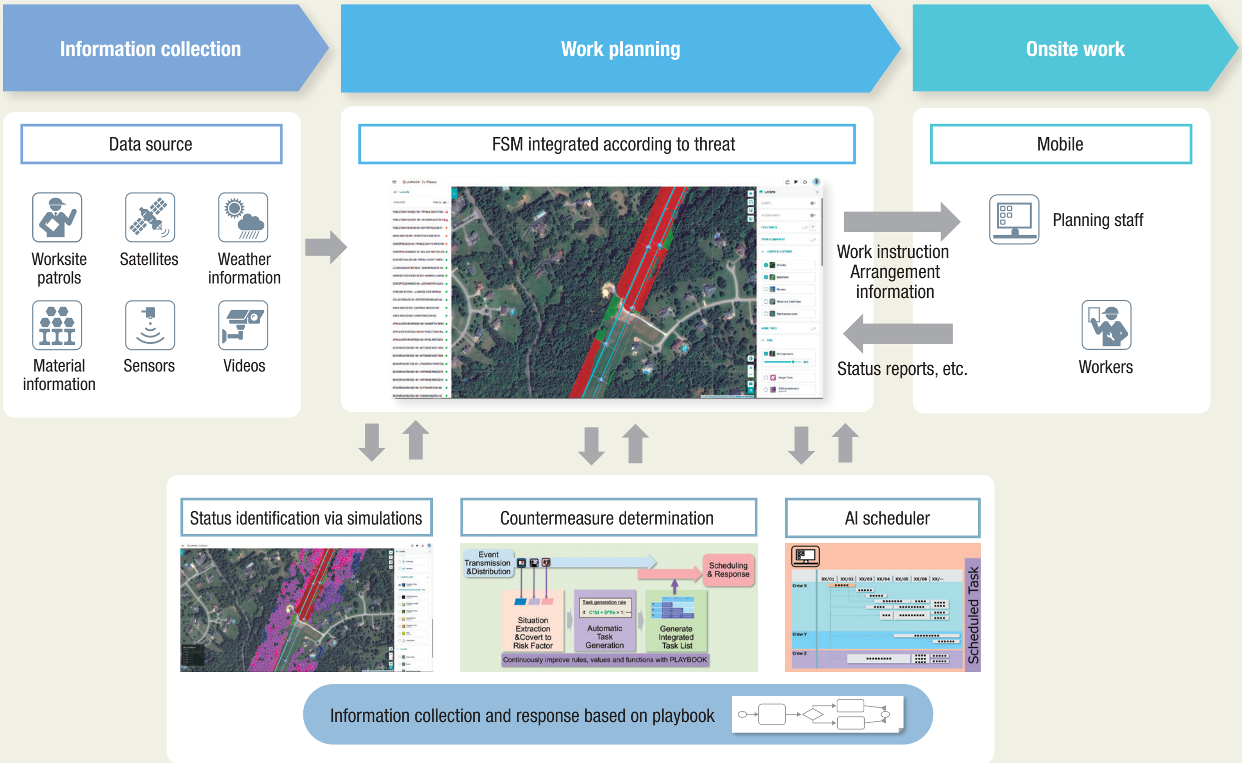
To improve the effectiveness of recovery capabilities, the creation and execution of an efficient and flexible recovery schedule for organizations, networks, and equipment is essential. The process is not completed after creating a schedule just one time. Rather, continuous rescheduling is required according to on-going incidents and changes in the response status, which is a key reason for using digital technology.

Figure 6 shows the concept of digitalization in field service management (FSM) that applies a digitalization framework to the objective of improving recovery capabilities for resilience. The aim is to enable a response to sudden, unexpected, and uncertain incidents, as well as faster and more efficient daily work. Hitachi has actually started to provide a service that collects remote sensing information via satellites to detect overgrown trees that may come in contact with power lines[7].

Based on this framework, Hitachi in the future will also use AI in systems for updating rules according to the accumulated field data and evaluations, and will also continue to expand solutions for total resilience countermeasures for power systems, including networks and equipment.

Figure 6 | Concept of Digitalization in Field Service Management for Resilience

The aim is to establish FSM that flexibly integrates functions to enable a response to sudden, unexpected, and uncertain incidents, as well as faster and more efficient daily work. Functions such as remote sensing via satellites and AI schedulers are combined according to the details of the threat.



FSM: field service management

Conclusions

This article has described the resilience proficiency model and framework proposed by Hitachi in response to the trend of using digital technology in power systems, which are in a historic era of transition to carbon neutrality. The key points of this framework are the digitalization of information collection, the digitalization of incident response rules, optimization of responses, and automatic generation of schedules using AI.

In the future, based on this framework, Hitachi will expand Lumada solutions for flexible resilience countermeasures that use digital technologies to comprehensively integrate organizations, networks, and equipment. This will help resolve the various issues faced by customers and create new businesses that contribute to strengthening resilience.

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FEATURED ARTICLES

Power Grids for a Sustainable Energy Future

As the use of natural energy sources such as solar and wind power continues to expand in the pursuit of decarbonized power generation, power transmission technologies that enable the optimal and efficient use of renewable energy have become a vital part of achieving a sustainable society. These featured articles describe examples of Hitachi initiatives and case studies that support energy supply and utilization. Hitachi's efforts include the development of high voltage direct current (HVDC) power transmission and control technologies suitable for the highly efficient and easily controllable transmission of power over long distances; the reduction of greenhouse gases involved in power transmission across the energy value chain; and the expansion and restoration of substations that support stable power grid operations.

Enhancement of Higashi-Shimizu Substation of Chubu Electric Power Grid by VSC Technology

In response to issues encountered after the Great East Japan Earthquake, projects are underway to expand the grid interconnection capacity between the different frequencies in eastern Japan (50 Hz) and western Japan (60 Hz). In April 2019, Hitachi, Ltd. received an order from Chubu Electric Power Grid Co., Inc. for the delivery of two blocks of frequency converter system at the Higashi-Shimizu Substation and for services such as equipment installation and testing. The aim is to start operation by the end of FY2027, with the interconnection capacity increased from the current 300,000 kW to 900,000 kW. The core equipment in this system, an AC-DC converter, will be the first back-to-back frequency converter in Japan to apply voltage source converter (VSC) technology. This new technology enables a black start that supplies power even when there are power failures during large-scale natural disasters, and the independent control of the active power and reactive power of the power grid. The technology is expected to be effective for stabilizing the power system. This article describes an overview of the project and the converter.

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1. Introduction

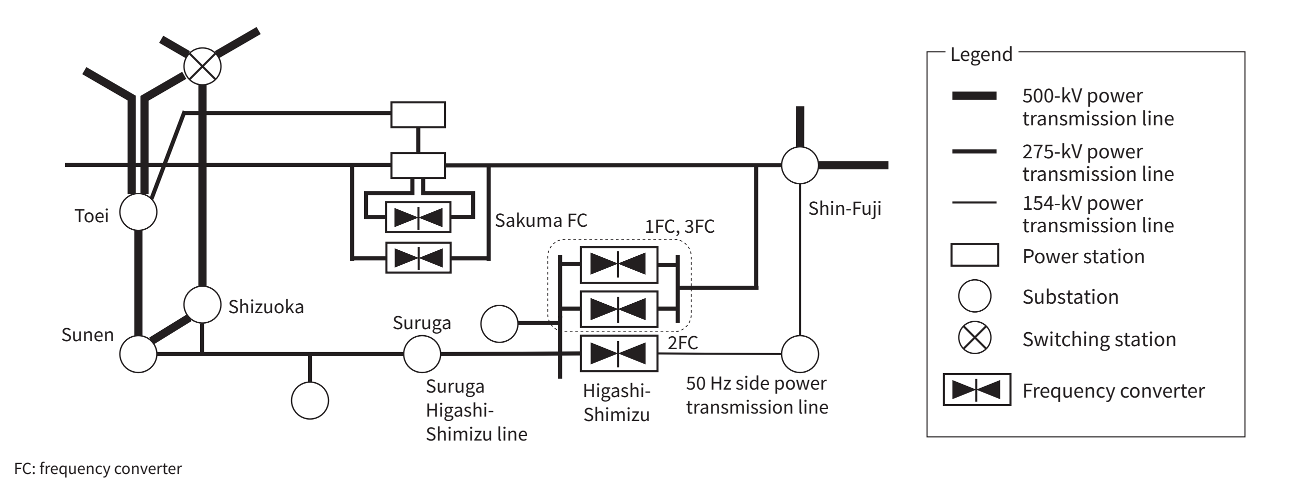
High-voltage direct current (HVDC)[*1] power transmission systems are attracting attention worldwide as a solution that supports the expansion of renewable energy as a main source of electric power, thus helping to achieve a decarbonized society. HVDC not only improves the resilience of the existing grid, but also has such advantages as reducing power transmission loss compared to alternating current (AC) systems, and enabling construction in a short period of time using techniques such as undersea cables. As a result, in Europe, which has been a pioneer in the large-scale deployment of offshore wind power and other renewable energy sources, cost-benefit analyses and other reports have shown many cases where the economic rationality of strengthening interconnection using HVDC is superior to using AC systems. This technology has benefitted from large-scale investment, leading to an HVDC market that is booming like never before.

Hitachi has been involved in nearly all HVDC projects in Japan since the development of HVDC in 1970. The year 2015 was a major turning point as Hitachi established Hitachi ABB HVDC Technologies, Ltd. as a joint

*1 This technology is primarily used to transmit power between two power grids. The electric power on the transmission side is converted from AC to DC and then the power is converted back to AC on the receiving system side. The reduced electrical loss, installation space, and construction costs make this the optimal technology for applications such as long-distance power transmission, and suitable for interconnecting grids with different frequencies, which cannot be connected directly when using AC.

Figure 1 — Power Grid Near Higashi-Shimizu Substation

Currently, the 60 Hz side is interconnected with the existing No. 2 FC via the 275-kV Higashi-Shimizu line from the Suruga Substation of Chubu Electric Power Grid, and the 50 Hz side is interconnected with No. 2 FC via the 154-kV power transmission line. This project will construct a new 275-kV power transmission line on the 50 Hz side and interconnect it with the newly-installed No. 1 FC and No. 3 FC.



venture with the power grids business of the Swiss-Swedish electrical engineering conglomerate, Asea Brown Boveri (ABB) Ltd. (what is now Hitachi Energy Ltd.) in order to expand HVDC business in Japan. The business has since been renamed Hitachi HVDC Technologies, Ltd. The company has steadily built up a record of achievements in Japan, and in 2021, through a joint venture, it delivered Japan's first overseas-made air-insulated filter for HVDC systems to the Hida Converter Station of Chubu Electric Power Grid Co., Inc.

2. Enhancing Interconnection Facilities between Tokyo and Chubu

The Great East Japan Earthquake on March 11, 2011, resulted in large-scale power loss in areas supplied by power companies in the Tohoku and Kanto regions. However, the amount of power interchange from power companies in other areas was limited due to restrictions in the interconnection capacity. This meant that rolling blackouts became unavoidable in some areas of the Kanto region. In view of this experience, the Organization for Cross-regional Coordination of Transmission Operators (OCCTO), Japan, which supervises power interchanges between power companies, identified the enhancement of grid interconnection capacity to achieve wide-area grid operations that go beyond the borders of individual areas as the most important challenge that they faced. Projects are underway for enhancing the interconnection capacity between the 60 Hz Chubu Electric Power Grid area and the 50 Hz area from the initial 1.2 million kW[*2] to 3 million kW. The Higashi-Shimizu Substation was selected as one of the frequency converters (FCs) to enhance, and facility owner Chubu Electric Power Grid was selected as the entity to implement the enhancements. After submitting technical proposals and quotations over a long period from 2017, Hitachi finally received the order in April 2019.

Among the FC facilities, Hitachi was given responsibility for the overall engineering of the system, the design and manufacturing of converter transformers, installation work for equipment, and system integration such as grid interconnection testing. Hitachi Energy is providing the main circuit equipment and control and protection systems, such as the converter valve that forms the core technology of the facilities.

This article describes the features of the main systems delivered by Hitachi, which were optimized according to the unique specifications and conditions of the Higashi-Shimizu Substation.

3. Basic Information about the Project

The Higashi-Shimizu Substation of Chubu Electric Power Grid is located in the Shimizu Ward of Shizuoka City, Shizuoka Prefecture, and is the third substation in Japan to contain FCs.

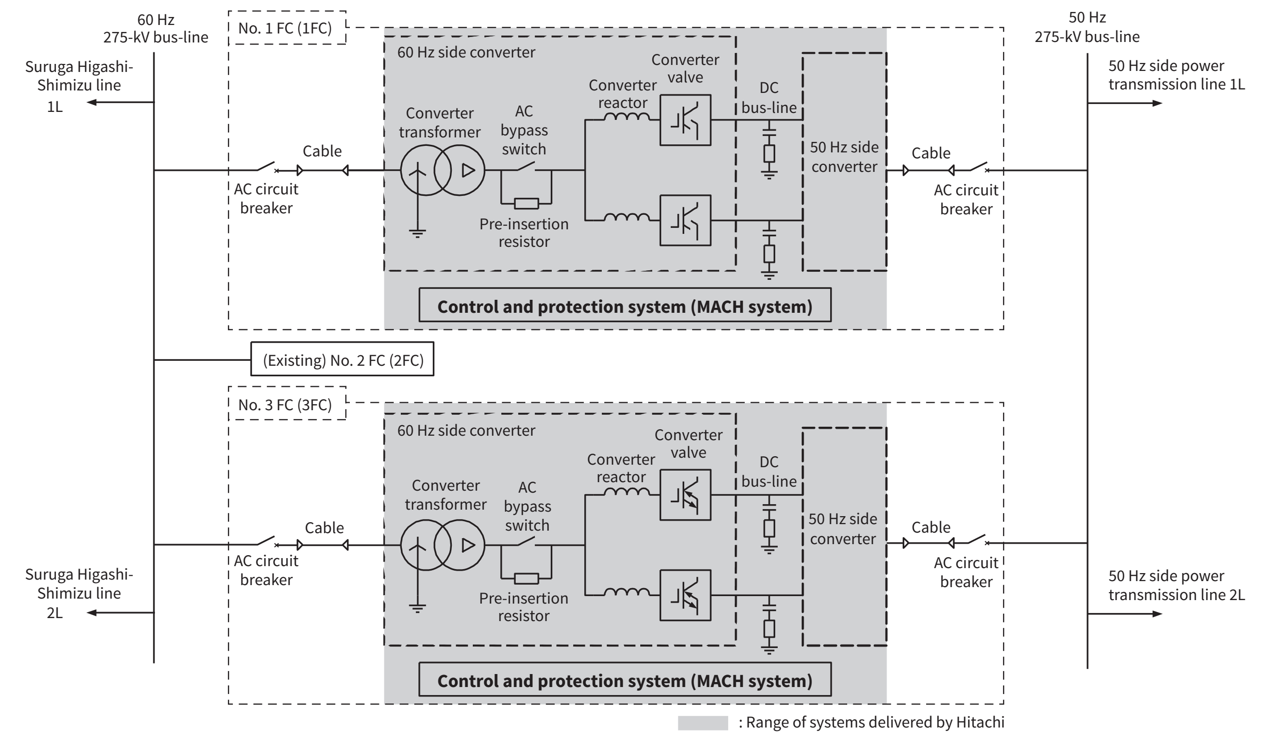
Figure 1 shows a diagram of the power grid. Currently, the 60 Hz side is interconnected with the existing No. 2 FC via the 275-kV Suruga Higashi-Shimizu line from the Suruga Substation of Chubu Electric Power Grid, and the 50 Hz side is interconnected with No. 2 FC via the 154-kV power transmission line. In this project, a new 275-kV power transmission line will be installed on the 50 Hz side, and this will be interconnected with the newly-installed No. 1 FC and No. 3 FC.

In the approximately four years since receiving the order for this project, Hitachi has made great efforts in various

*2 In 2021, the start of operations at the Hida-Shinano HVDC link increased capacity to 2.1 million kW.

Figure 2 — Main Circuit Configuration of Higashi-Shimizu Substation and Newly-installed No. 1 and No. 3 FCs

The AC side of each FC is connected from the 275-kV bus-line to the primary side of the converter transformer via a cable, and equipment that forms the AC-DC converter is installed on the secondary side. Each FC is controlled and protected by the MACH system.



MACH: Modular Advanced Control for HVDC L: line

* This figure provides an approximate image of the main circuit configuration of the substation, and does not indicate the actual configuration.

system studies, station layout plans, and finalizing the main circuit specification. Fully fledged engineering and civil construction work started at the substation in 2022. Hitachi has started manufacturing the equipment in 2023, and will install the equipment starting from 2024.

The next section describes an overview of the HVDC system and the features of the main circuit equipment including converter valve and control and protection systems.

4. System Design

4. 1 Main Circuit Configuration

Figure 2 shows the main circuit configuration of the Higashi-Shimizu Substation, including the No. 1 and No. 3 FCs that will be newly installed. Both FCs will be connected to the 275-kV bus on the 60 Hz side to the 275-kV bus on the 50 Hz side. Each FC has conversion capacity of 300 MW rated active power and ±100 Mvar rated reactive power, and they are configured as a back-to-back (BTB) system using HVDC Light, Hitachi Energy's self-commutated[*3] converter. **Figure 2** shows the main circuit configuration representing the converter on the 60 Hz side, but the same is also used for the converter on the 50 Hz side. The No. 1 FC and No. 3 FC are independent FCs, and each is in a symmetrical monopole configuration. Also, for the 275-kV bus on the 60 Hz side, the existing No. 2 FC is interconnected in parallel (the interconnection to the 154-kV bus-line on the 50 Hz side is omitted from the figure). The scope to be delivered by Hitachi is shown within the shaded area of **Figure 2** including the converter transformer and its secondary side (converter side) AC/DC equipment, and the control and protection systems.

The AC bus is connected to the primary side of the converter transformer via an AC circuit breaker and a cable. The converter transformer is composed of Y-Δ windings and the primary side is grounded directly. Converter reactors and converter valves for both the positive and negative poles are connected to the secondary side of the converter transformer via an AC bypass switch and pre-insertion resistor. The DC bus is equipped with a pole capacitor and a DC damping resistor, which maintain the ground potential balance of the positive and negative DC poles while reducing the ripple voltage that accompanies valve switching.

*3 This is an AC-DC conversion system that uses a self-commutated power electronic switching device. Compared to other line commutated converter technology using thyristors, the advantages of this system include more compact equipment and enabling diverse and complex controls, which greatly improves the reliability of the power grid.

A control and protection system called Modular Advanced Control for HVDC (MACH) is provided for both the No. 1 and No. 3 FCs. It controls apparatuses such as the AC circuit breaker, AC bypass switch, and converter valves, while also controlling auxiliary equipment that is not shown in the figure, such as the valve cooling system.

4. 2 Specifications of AC-DC Converter and Converter Valve

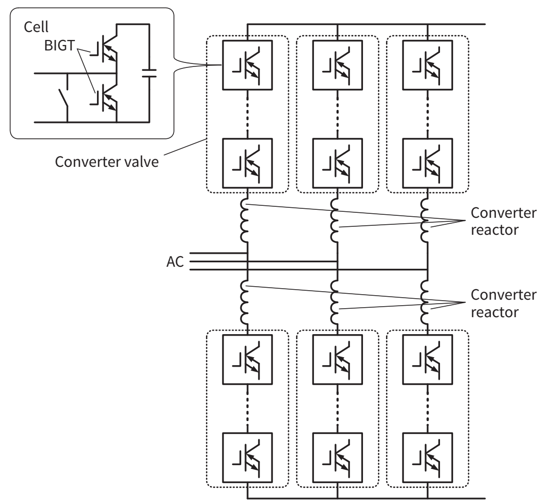
In this FC, a modular multilevel converter (MMC) is used as the AC-DC converter. **Figure 3** shows the configuration and main specifications of the AC-DC converter.

An MMC is an AC-DC converter circuit based on arms composed of identical cells (also called submodules) connected in series. The arms are connected in a three-phase bridge to form the AC-DC converter. A feature of an MMC is its high scalability in terms of capacity and voltage, which can be varied by increasing or decreasing the number of cells. The standard lineup of Hitachi Energy's HVDC Light supports voltages and capacities up to the ±640-kV class and 4,000-MW class. In this project, factors such as the grid voltage and frequency variations have been considered to design the valve configuration and the main circuit parameters that satisfy the required capabilities of 300 MW and 100 Mvar.

Bi-mode insulated gate transistors (BIGT) of a 5.2 kV withstand voltage are used as the power semiconductor devices in the cells. A BIGT is a semiconductor device that combines the functionality of a conventional insulated gate bipolar transistor (IGBT) and a free-wheeling diode on a single semiconductor chip, and is thus a type of a reverse conducting IGBT. Since the IGBT current and the diode current flow on the same chip, the chip has benefits for balancing heat generation and heat dissipation, making it suitable for higher currents. In this project, two BIGTs are used in each cell to form a chopper cell.

Figure 3 — Configuration of AC-DC Converter

The AC-DC converter has an MMC configuration where each cell is a chopper cell using BIGT.



MMC: modular multilevel converter BIGT: bi-mode insulated gate transistor
AC: alternating current

4. 3 Overview of Operation Control Methods

(1) Basic functions and FRT capability

The basic functions of this FC are automatic power regulator (APR) for interchange power control, alternating current - automatic voltage regulator (AC-AVR) for AC voltage control, and automatic reactive power regulator (AQR) for reactive power control. In addition, the FC is equipped with special functions, such as emergency power presetting switch (EPPS) for supporting AC grids whose frequency drops excessively, over-frequency control for supporting AC grids whose frequency rises excessively, and transfer block control. If an AC faults such as a grounding or short-circuit fault occurs in an AC grid, operation continues without gate blocking, which is known as the fault ride through (FRT) capability. Furthermore, a function is provided that injects reactive current in order to support grid voltage during a grid fault. **Figure 4** shows an example of analysis after a three-phase grounding fault (3LG) occurred near the Higashi-Shimizu Substation of the Suruga Higashi-Shimizu line on the 60 Hz side (the figure shows only the waveform of the No. 1 FC). Before the fault occurred, active power was interchanged at 300 MW toward the east. The figure shows that when a 3LG occurs, the voltage at the point of common coupling drops to almost zero, but the converter continues operating without gate blocking, reduces the active current, and injects reactive current. When the grid fault is cleared, power interchange of 300 MW can be restored promptly.

(2) Functions that take advantage of the self-commutated converter features

This project provides an islanded operation function and a black start function (for starting up after a black out) that take full advantage of the features of the self-commutated converter.

After a certain type of a grounding or a short-circuit fault in the 60 Hz grid is cleared, the grid on the Shizuoka side may be isolated from the main grid, forming an islanded grid composed of only the FC and the loads. With the islanded operation function, the No. 1 and No. 3 FCs switch from interchange power control to islanded operation mode for the load on the resulting islanded grid, thus continuing to supply electricity as the voltage source.

In the black start function, if either the 60 Hz grid or 50 Hz grid blacks out, the converter is started using the energy of the healthy grid and the function ramps up the voltage on the blackout AC system. This enables the converter to be used as the starting point for restoring the blacked out system.

Figure 4 — Example of Analysis of Three-phase Grounding Fault Near Higashi-Shimizu Substation on 60 Hz Side

The analysis confirmed that even if a malfunction such as a short circuit or grounding fault occurs on the AC grid side, the converter can continue operation without gate blocking. Also, reactive current is input while the grid failure continues to contribute to power grid stabilization.

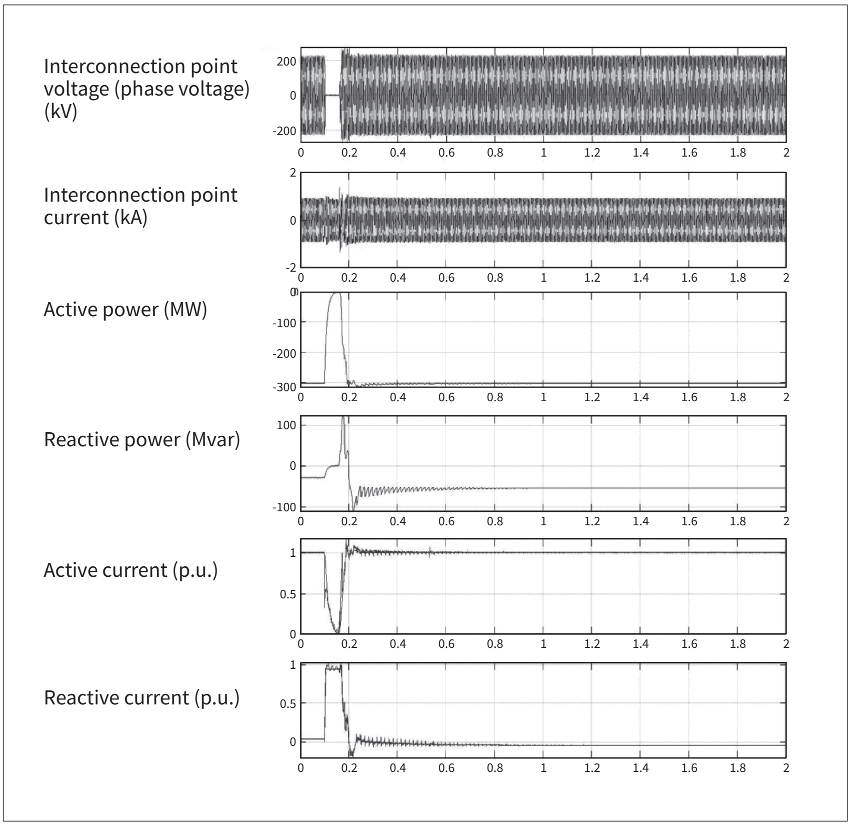
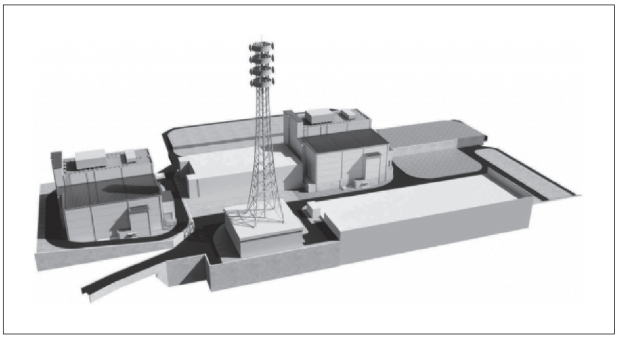


Figure 5 — Image of Frequency Converter Building (No. 1 FC, No. 3 FC)

The figure shows the No. 3 FC (left), No. 2 FC (center), and No. 1 FC (right). After completion, the building will have one underground floor and two floors above ground, and the building height will be about 25 m above ground.



The control and protection system (MACH system) that performs the operation controls described above has redundancy for both the control and the protection computers, with standby redundancy for control and parallel redundancy for protection. The control system in operation can also be switched to the standby side without gate blocking.

4. 4 Layout

A feature of the Higashi-Shimizu Substation is its compact size, located on a steep hillside. **Figure 5** shows an image of how the substation will look after the completion of the building construction. The existing No. 2 FC is at the center, with the No. 3 FC newly constructed on the north side and the No. 1 FC on the south side. Due to the limited space at the substation site, it was difficult to devise an efficient equipment layout that maintained the required electrical and maintenance work clearance during a phase where the equipment design had not yet been finalized. Engineering and construction staff collaborated frequently to design a building that would not hinder the actual equipment installation work or the maintenance work after the start of commercial operation.

5. Conclusions

This article described the No. 1 FC and No. 3 FC at the Higashi-Shimizu Substation whose operation is scheduled to start at the end of FY2027, and the specifications and features of the frequency converters and equipment that will be delivered by Hitachi.

Hitachi positions HVDC as one of its core businesses within the energy field, and in the future, Hitachi will continue to meet demand for grid interconnection facilities that accompany the enhancement of grid interconnection and growth of renewable energy both in Japan and overseas, thus contributing to the achievement of a decarbonized society.

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Rapid Restoration of Unit No. 8 Generator Step-up Transformer at Nakoso Power Station

The stable supply of electric power requires a minimum reserve rate of 3%. However, ever since the Great East Japan Earthquake in 2011, the margin between the supply and demand of electricity in Japan has been tight. When demand for electric power increases due to extremely hot or cold weather and the risk grows of not securing the 3% reserve rate, the authorities issue a power crunch warning or alert. It was in this context that on September 16, 2021, a failure due to aging forced the emergency stop of the unit No. 8 generator step-up transformer (built in 1981) at the Nakoso Power Station of Jōban Joint Power Co., Ltd. This shut down the supply of 600,000 kW of electric power, which is equivalent to about 1% of the total demand peak in the Tokyo area. Hitachi, Ltd. received a request from the customer for the rapid restoration of the power station to help stabilize the power supply in Japan. In a project that would normally take more than a year to deliver from receiving the order to transmitting power, all stakeholders came together as a team to complete the work in about 9 months.

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1. Introduction

The proportion of Japan's annual power generation capacity taken up by thermal power generation has decreased steadily since the oil crisis in the 1970s. But since the Great East Japan Earthquake in 2011, the proportion increased as thermal power generation replaced nuclear power generation. Then, the proportion of thermal power started to decrease again as the use of renewable energy expanded and some nuclear power stations were restarted; even so, it still makes up about 70% (about 700 billion kWh) of the power supply in Japan.

Of this 70%, the Nakoso Power Station of Jōban Joint Power Co., Ltd., a complex containing three power generators (unit No. 7 generator: 250,000 kW, unit No. 8 generator: 600,000 kW, and unit No. 9 generator: 600,000 kW) provides an amount of power equivalent to about 1% of Japan's thermal power generation (7 to 10 billion kWh annually) to the Tohoku and Tokyo areas. However, on September 16, 2021, a failure due to aging forced an emergency stop of the unit No. 8 generator step-up transformer (GSUT) at Nakoso Power Station. This shut down the supply of 600,000 kW of electric power, which is equivalent to about 1% of the total demand peak in the Tokyo area. In response, Hitachi was requested to conduct rapid restoration work to restart the power generation and help secure the reserve rate of 3%.

2. Overview of Restoration

Figure 1 shows the main circuit configuration around the unit No. 8 GSUT of the Nakoso Power Station that was subject to this restoration project.

After receiving notification about the failure of this transformer, Hitachi quickly dispatched inspectors to the site to investigate the cause of the failure and start considering methods for rapid restoration. Hitachi considered the restoration methods of onsite repair, offsite repair, replacement with a spare from another power plant, or manufacture of a new transformer. Hitachi submitted a report to the customer that detailed the work schedule and various conditions for all of these restoration methods, as well as the results of the cause of failure investigation. After discussing these results together, the customer selected the rapid restoration proposal based on replacing the transformer with one that would be newly manufactured. Hitachi conducted an additional investigation into the cause of failure and considered countermeasures to prevent the same incident from occurring with the new transformer.

Two proposals were considered for where to manufacture the new transformer; at the Hitachi Works Kokubu Factory (Kokubu Factory) or at the Chongqing Factory of Hitachi Energy (China) Ltd. (Chongqing Factory). In this project, since Hitachi received consent from the customer to re-examine some of the existing interfacing parts, the Kokubu Factory was selected because it owns the existing

Figure 1 — Schematic Diagram of Nakoso Power Station

In this project, Hitachi worked toward the rapid restoration of the unit No. 8 GSUT.

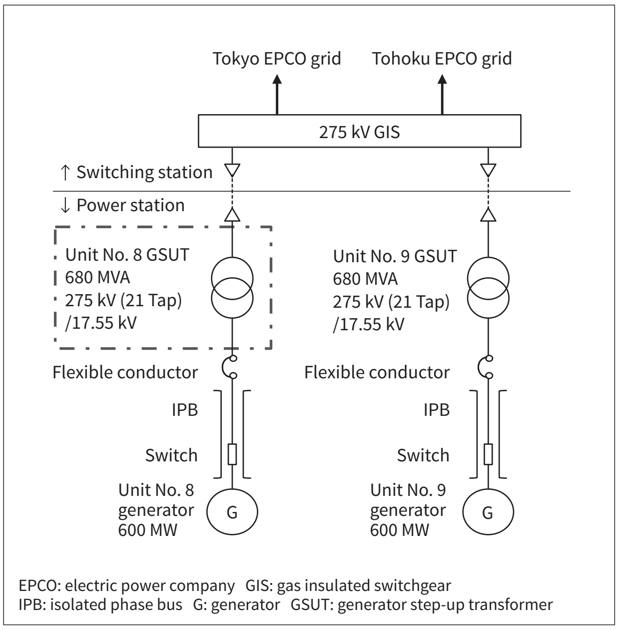
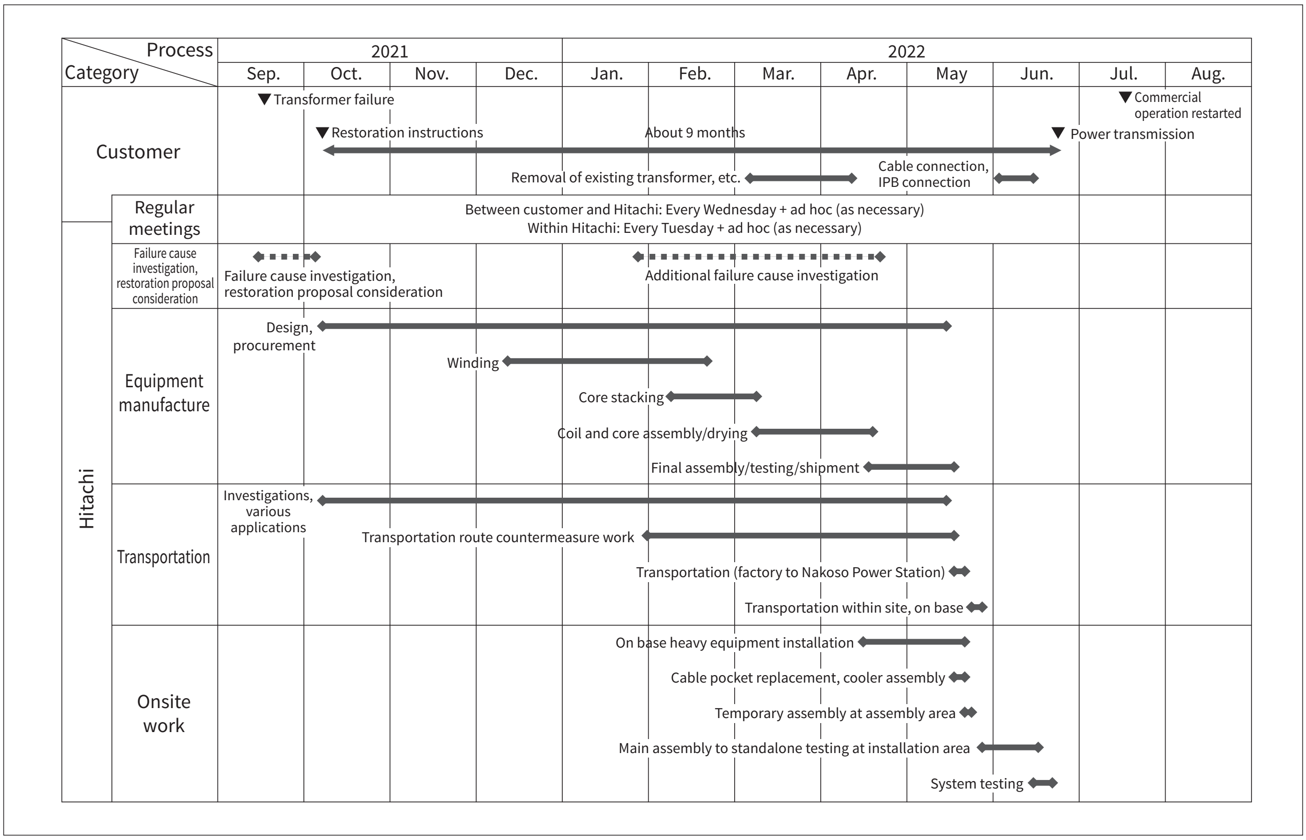


Figure 2 — Overview of Restoration Process Results for Unit No. 8 GSUT

In addition to investigating the causes of the failure immediately after the failure occurred, Hitachi considered various rapid restoration methods and completed the project in about 9 months; normally, the process from receiving the order to transmitting power would take more than a year to deliver.



design. Although the Chongqing Factory was not selected due to transportation times and conditions, the high level of its product manufacturing capacity was confirmed, with almost no difference from the Kokubu Factory, even when considering the new design and the manufacturing period for all the new parts.

Hitachi shortened the process while sharing and consulting with the customer about the risks and opportunities inherent in rapid restoration across the entire project, including manufacturing, transportation, and construction work. This enabled Hitachi to complete the project from receiving the restoration instructions to transmitting the power in a very short delivery time of about 9 months (see **Figure 2**).

This article describes how Hitachi was able to cope with such a short delivery time while ensuring quality and avoiding accidents.

3. Coping with the Short Delivery Time

This section describes the actions Hitachi took to achieve the short delivery time.

3. 1 Project Setup

Immediately after receiving the restoration instructions, Hitachi appointed its internal project members (from the business unit and design, procurement, manufacturing, quality assurance, transportation, and construction departments) and set up regular meetings (within Hitachi: every Tuesday, between the customer and Hitachi: every Wednesday). This created a system that could confirm the progress of work in a timely manner. Hitachi also held ad hoc meetings if any urgent matters were discovered to ensure actions could be taken without delay to avoid risks (process delay or malfunctions) or to make the most of opportunities (shortening the process).

3. 2 Design, Procurement, and Manufacturing Measures

(1) Repeated existing design

Repeating the same design as the existing plant enabled the design time to be shortened compared to completely new manufacturing.

Figure 3 — Overview of Transformer Manufacturing Flow

The process for winding, core stacking, core assembly, final assembly, factory testing, and readying for delivery was shortened via measures such as overtime and day and night work shifts.

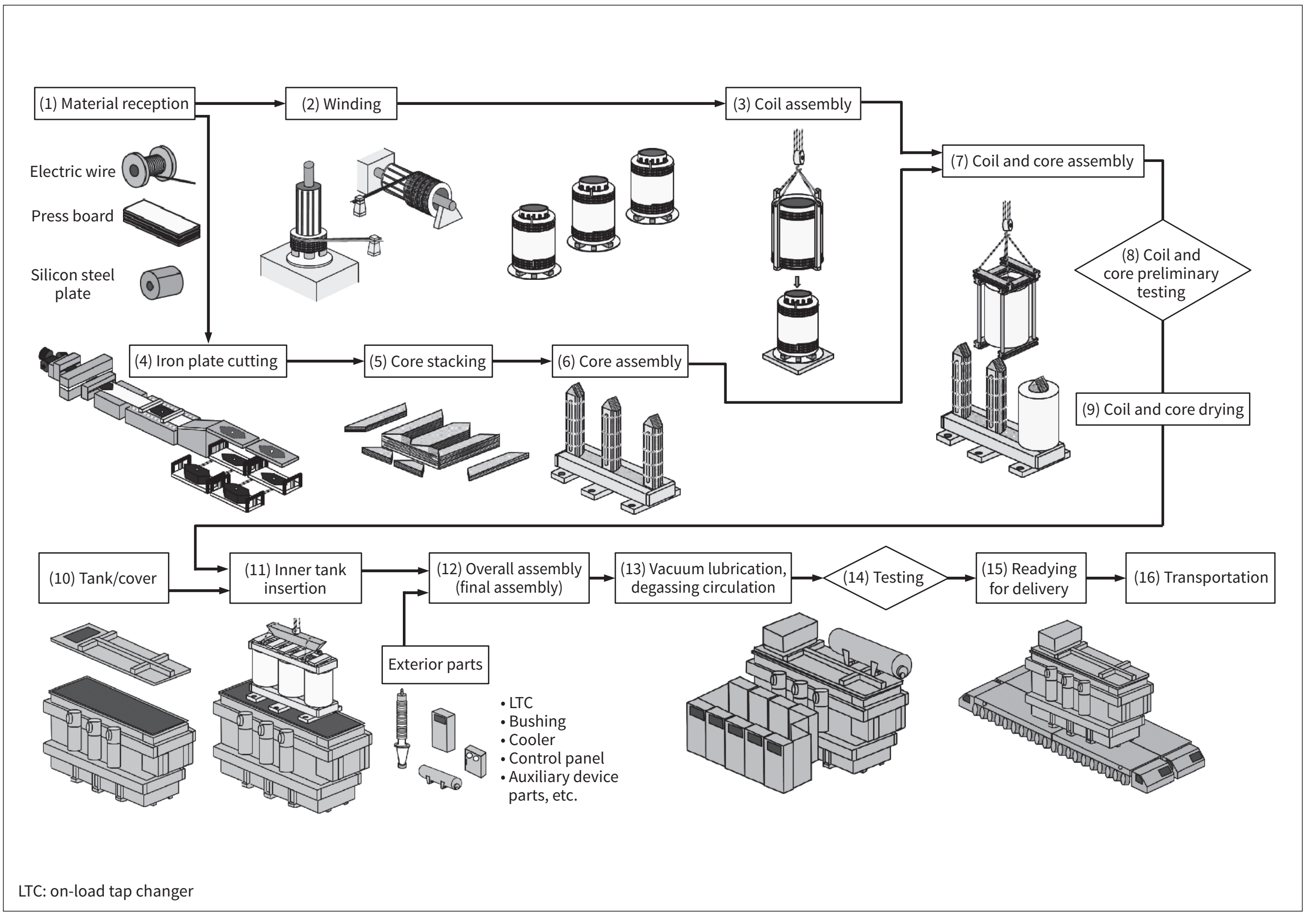
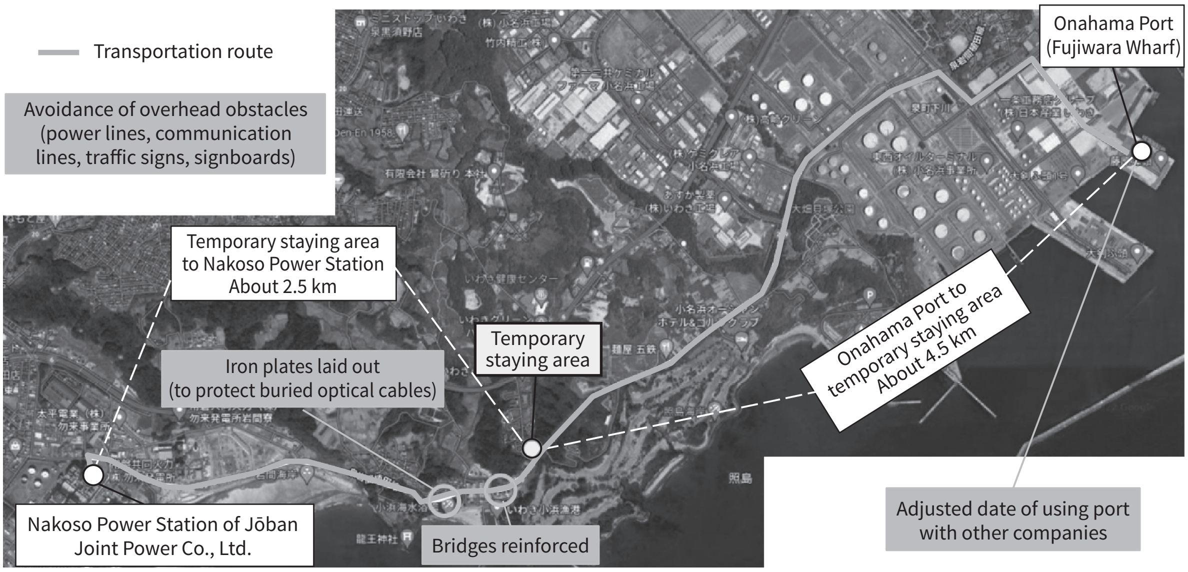


Figure 4 — Transportation Route from Onahama Port to Temporary Staying Area to Nakoso Power Station

The overall process from factory shipment to arrival on site was performed in the following order: May 19 (Thursday), night-time transport on public road (Hitachi Works Kokubu Factory to Hitachi Port); May 20 (Friday) 6:00 to 9:30, ship loading (Hitachi Port); 9:30 to 12:30, sea transport (Hitachi Port to Onahama Port); 12:30 to 17:30, unloading from ship (Onahama Port); May 21 (Saturday) 3:00 to 6:00, transport on public road (Onahama Port to temporary staying area); 6:00 to 10:00, waiting (temporary staying area); 10:00 to 12:00 transport on public road (temporary staying area to Nakoso Power Station).



(2) Increased personnel in initial stage of design

Hitachi requested the support of partner companies to increase the speed of creating design plans, arranging materials, and issuing manufacturing instructions.

(3) Delivery times backed up through dual design of parts used

While implementing Plan A, which used all new parts, Hitachi also considered Plan B in parallel, which refurbished and re-used parts that had long delivery times (such as oil level gauges, low-voltage bushings, and resistance thermometers). This hedged the risk if there were any delays in Plan A.

(4) Identified the shortest supply routes

(a) Core materials and cutting process (supplier selection)

Initially, Hitachi expected to use suppliers within Japan, but due to uncertainty in the status of arranging processing equipment, this was switched to an overseas supplier to mitigate the risk of late delivery.

(b) Transportation method for on-load tap changer (LTC), a part procured from overseas

Initially, Hitachi expected to use sea transport, but this was changed to air transport to meet the shortened manufacturing schedule at the site, thus avoiding any interruption of the manufacturing process.

(5) Adjusted the manufacturing process

Various process-shortening methods were considered, according to factors such as onsite loading and material receiving status, and the factory shipment date was moved forward from the initially expected date in the middle of June to May 19, shortening the delivery by about a month (see **Figure 3**).

3. 3 Adjustment of Transportation Process

3. 3. 1 Transportation Overview

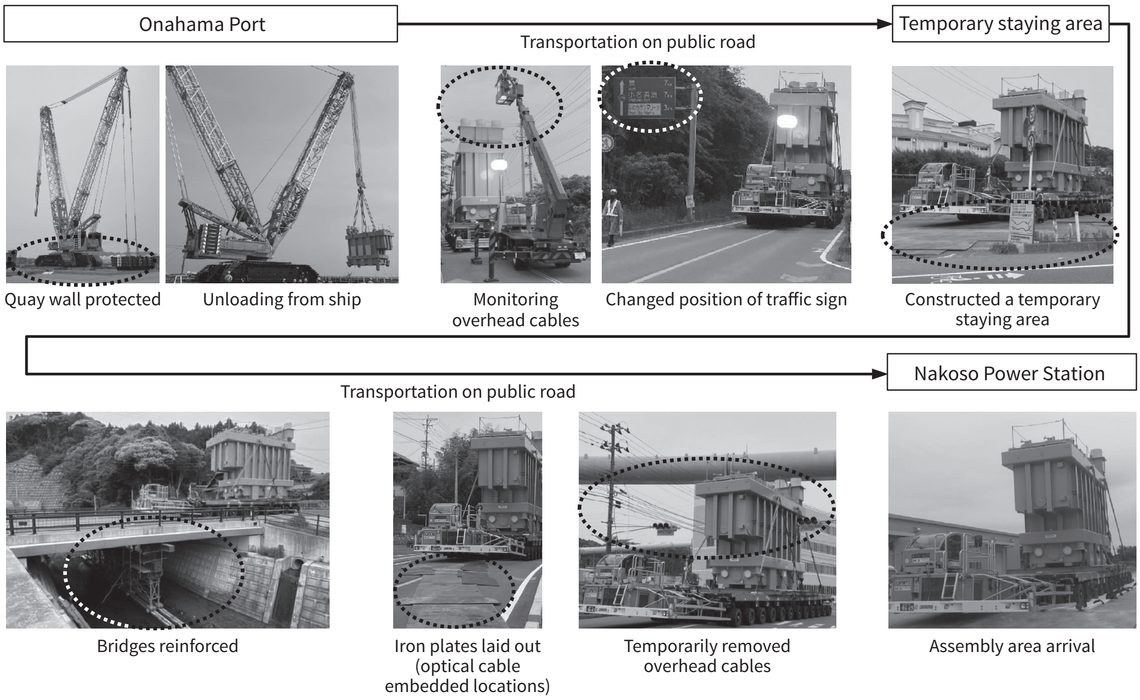
The transportation of the transformer in this project was performed overland from the Kokubu Factory to Hitachi Port, by sea from Hitachi Port to Onahama Port, and then overland from Onahama Port to Nakoso Power Station (see **Figure 4**).

3. 3. 2 Mitigation Measures and Adjustments with Stakeholders

Even after removing the exterior parts for transportation, the weight of the transformer in this project was 290 t and the stacked height on the vehicle was more than 9 m, making it extremely large equipment. This meant that mitigation measures were required along the transportation route to protect objects buried underground, avoid overhead obstacles, and reinforce bridges. Because there is no quay wall for unloading from a ship at Nakoso Power Station, mitigation measures were required across a wide range, not only on the public road from the Kokubu Factory to Hitachi Port, but also on the public road from Onahama Port to Nakoso Power Station (see **Figure 5**).

Furthermore, as the factory shipment date was pushed forward, the mitigation process was shortened, necessitating many negotiations with stakeholders related to the roads,

Figure 5 — Photographs of Transportation Route from Onahama Port to Temporary Staying Area to Nakoso Power Station
The areas shown in the ovals were the subjects of countermeasures.



vehicles, ports, shipping lanes, ships, heavy machinery, and other areas used for transportation. Usually, the route from the Kokubu Factory to Hitachi Port can only be used at night on Friday. Hitachi needed to negotiate with local citizens, local government, and the police to obtain special permission to travel the route at night on Thursday. Hitachi arranged the schedule so that the ship loading, sea transportation, and ship unloading, which would normally take three days, could be completed on the same day. This avoided work on Sunday, which is prohibited in principle under local restrictions, for unloading the ship at Onahama Port and the transportation on the public road from Onahama Port to Nakoso Power Station. These actions shortened the time from factory shipment to arrival at the site from the normal five days to three days, which was an unprecedentedly short transportation time.

3. 3. 3 Main Stakeholders for Large Equipment Transportation

(1) Kokubu Factory to Hitachi Port

The main stakeholders were the road administrators, overland transportation company, and transportation route countermeasure vendor.

(2) Hitachi Port to Onahama Port

The main stakeholders were the port administrators, ship loading vendor, sea transportation company, and ship unloading vendor.

(3) Onahama Port to Nakoso Power Station

The main stakeholders were the road administrators, overland transportation company, and transportation route countermeasure vendor.

3. 4 Adjustment of Construction Process

3. 4. 1 Adjustment of Work Procedures and Personnel Assignment

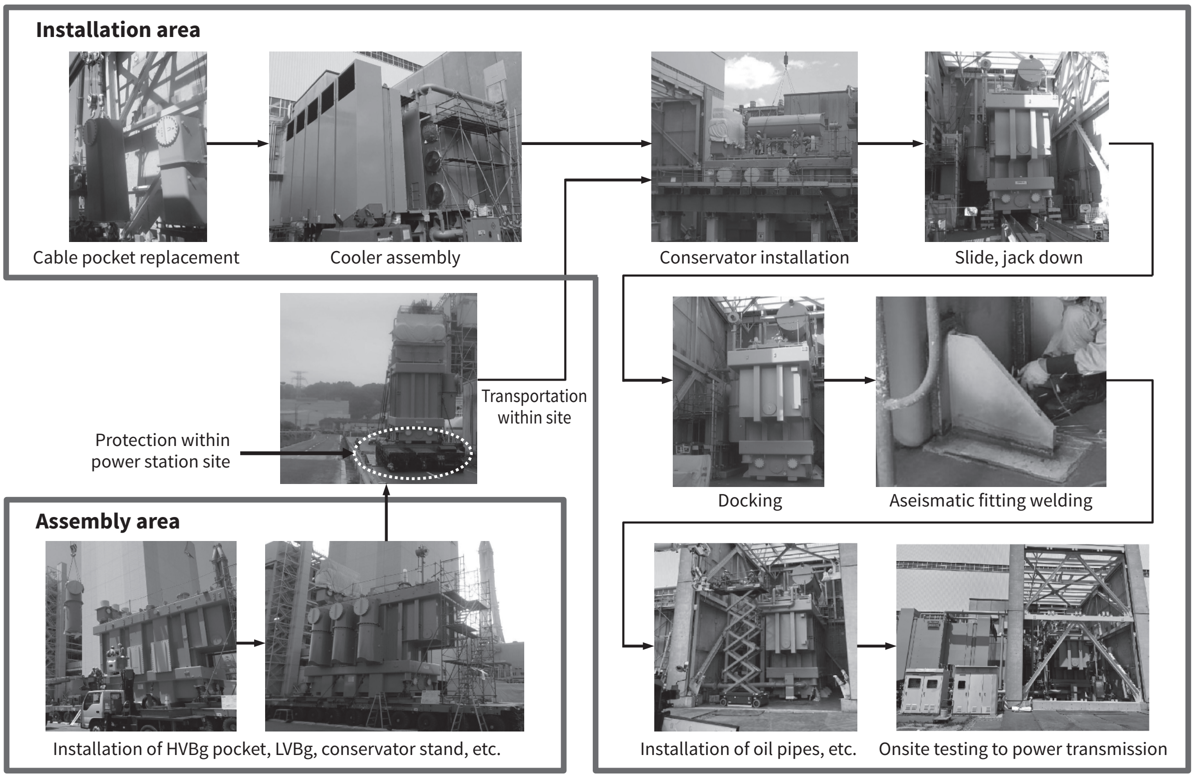
Hitachi held repeated discussions with the customer to shorten onsite processes in any way possible, even if only by one day. The process was shortened as much as possible through measures such as improving workability by dismantling the wall of the existing transformer building, and a wrapping process to secure empty space within the power station.

In the installation area, the cable pocket was replaced and the cooler was assembled before the main unit was placed on the base. In parallel, the exterior parts were installed on the main unit in the empty space (assembly area) within the power station, and then the main unit was transported within the site to the installation area, enabling a smooth transition to the next process (see **Figure 6**).

Furthermore, an onsite system was constructed for work on holidays and in day and night shifts by borrowing personnel from other projects and increasing the number of workers from partner vendors. Other actions included reassigning various workers to meet the shipment date that was pushed forward and coordinating with the customer's

Figure 6 — Photographs of Onsite Assembly and Installation Work

Hitachi devised the shortest possible process by improving workability (dismantling the wall of the existing transformer building), performing work before placing the main unit on base (cable pocket replacement, cooler assembly), and performing a wrapping process using empty space (exterior part installation).



HVBg: high-voltage bushing LVBg: low-voltage bushing

work schedule. This enabled the entire work process from equipment arrival to power transmission to be completed with almost no interruptions.

3. 4. 2 Process Adjustment for System Testing and Advance Arrangements

Normally, system testing is often performed together after finishing the equipment standalone testing. However, in this project, the transformer standalone testing that could be performed on the same day, such as LTC remote operation testing, confirmation of remote display of alarm failures, and current transformer (CT) polarity testing, were performed successively.

The cables used for system testing were laid out in advance between each testing location for a smooth transition to the testing process (see **Figure 7**).

Initially, there was not a single free day planned after the arrival of the equipment, but by continuing to explore every opportunity to shorten the process, the power transmission process that was scheduled for June 29 could be pushed forward by two days to June 27 due to system testing.

3. 4. 3 Main Stakeholders for Onsite Work

(1) Hitachi side

The main stakeholders were the construction workers, on base vendor, transportation route countermeasure vendor (protection of buried objects within site), transformer installation supervisors, transformer installation test inspectors, and system testing inspectors.

(2) Customer side

The main stakeholders were those involved in the advance work (such as existing transformer removal), cable connection, isolated phase bus (IPB) connection, fire hazard inspection, and the power supply department of the power company (arranged for the date of power transmission).

4. Quality Assurance

4. 1 Countermeasure for Potential Malfunctions

Although the existing design was repeated to achieve the shortest possible delivery time, there were some areas of

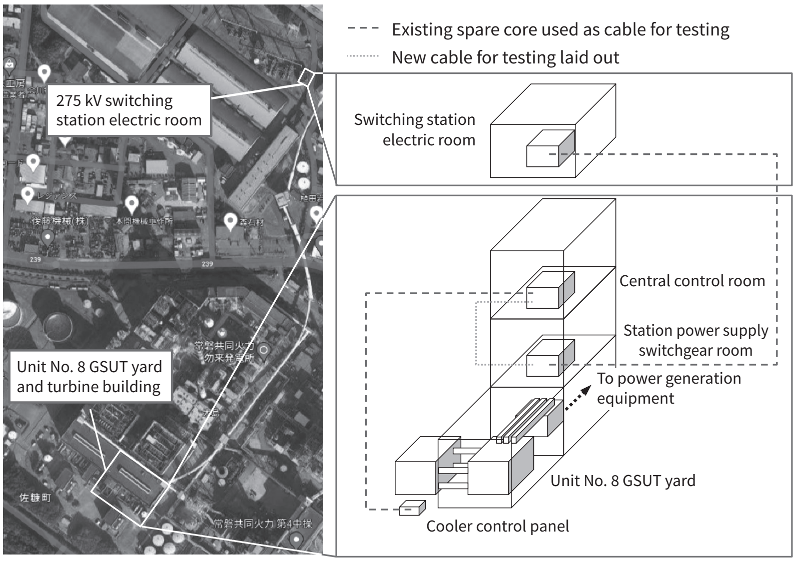


Figure 7 — Diagram of Cable Layout for System Testing at Site

A communication line (2 cores), standard line (2 cores), and matching phase detection line (1 core) were laid out. The results of an advance site investigation showed the need to lay out new cables for testing in sectors with no existing spare cores.

the 40-year-old design that could not be duplicated. The countermeasures for such areas were reviewed closely by experts as Hitachi made every effort to assure the quality of the new transformer.

4. 1. 1 Discontinued Parts

(1) Resistance thermometer

The manufacturer had discontinued the manufacture of the existing part, but a different manufacturer was found to produce an alternative (same specifications as the existing part).

(2) High-voltage bushing

The manufacturer had discontinued the manufacture of the existing part, but a different manufacturer was found to produce an alternative. Since the dimensions varied greatly from the existing part, areas such as the interfacing parts and the lead wire were re-examined.

(3) Steel material of main unit tank

The steel marine (SM) material of the existing unit is no longer used, so the current steel structure (SS) material was studied instead.

4. 1. 2 Differences between Initial Delivery and Present Time

(1) Main unit tank material transportation

A transportation compliance review showed that transportation with the same dimensions as the existing unit would not be possible. This resulted in a plate-mounted split structure for the main unit tank.

(2) Review of internal standards

To prevent the overheating of bolts and other parts by the current circulating through locations such as the cable pocket, a conductor for current energization was added to the flange and the welding structure was changed.

4. 1. 3 Matching Interfaces with Existing Cable Heads

Since it was necessary to match the interfaces with the existing cable heads, the dimensions at the site were measured and the structure was changed to one with plenty of allowance for adjustments, such as changing the bolt hole diameters and increasing the number of part divisions.

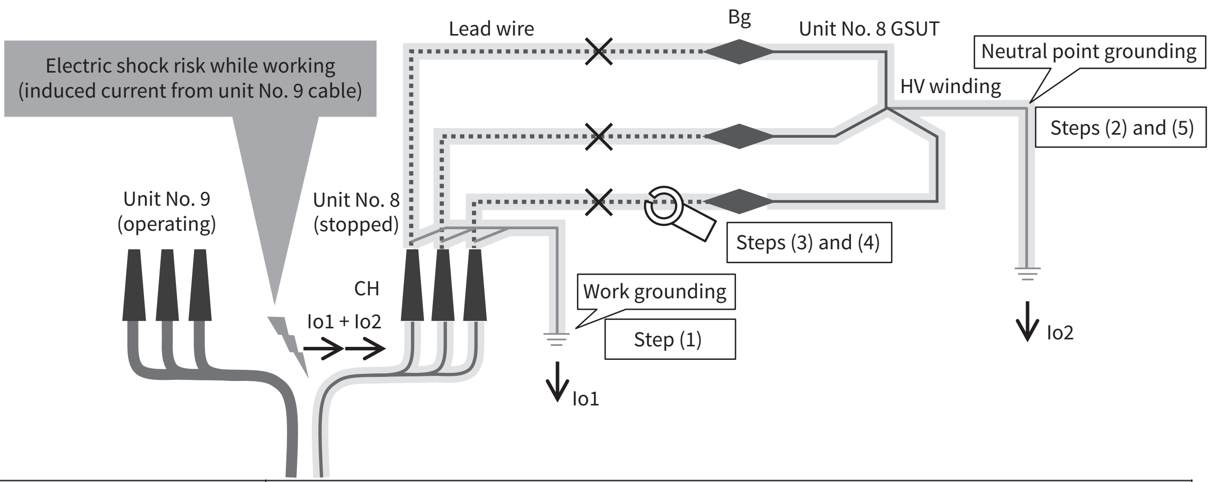
4. 2 Proposals for Future Preventive Maintenance

The results of the investigation into the cause of the failure of the unit No. 8 GSUT showed that a short circuit occurred between taps. This was caused by overheating and damage of the contacts on the LTC main unit tank side, due to aging. About 40 years had elapsed since this transformer had started operations and the number of LTC switches was about 120,000, which is approximately one quarter of the number of switches generally expected. From these facts, it was deduced that the failure was a phenomenon more likely to occur under the conditions of both “significant aging” and a “low LTC switching frequency.” (When surface roughness and level differences between specific contacts progress due to use in a limited tap range and the terminal position remains fixed, overheating occurs more easily due to deterioration of contact energization, carbon adhesion, and other factors.)

As preventive maintenance for the future, in addition to lifting inspections of the changeover switches on the regular maintenance menu, Hitachi added contactor inspections for the LTC segment (tap selection device, polarity switch) on the tank side of the transformer main unit in significantly aged equipment to the maintenance menu.

Figure 8 — Diagram of Induced Voltage Countermeasures

Measures were taken to reduce the induced current when disconnecting and connecting the lead wire between the transformer and cable heads, which reduced the risk of accidental electric shocks and allowed work to proceed.



Work timing	Actions
When disconnecting existing transformer lead wire	Reduce induced current by constructing detour circuit (procedure below) (1) Connect the grounding wire to the CH section (2) Disconnect the grounding wire connected to the neutral point (3) Measure the current flowing to the lead wire with a clamp meter (4) If there is no energized current or the current is low, cut the lead wire (× section) according to the worksite instructions (quality assurance staff) (5) After work, reconnect the grounding wire to the neutral point
When connecting new transformer lead wire	As above [in step (4), connect the lead wire] + Further reduce the induced voltage by limiting the output of unit No. 9 (from normal level of 500 MW to 250 MW during work)

HV: high-voltage side CH: cable head Bg: bushing

5. Prevention of Accidental Electric Shocks

During the work disconnecting the existing transformer from the cable heads, induced current from the adjacent operating unit No. 9 was observed. As a result, Hitachi considered countermeasures against electric shocks (see **Figure 8**).

Measures to reduce the induced current were taken by constructing a detour circuit when disconnecting the lead wire between the existing transformer and the cable heads. The results of subsequent verification also confirmed the effect of reducing the induced current by limiting the output of unit No. 9. Therefore, when connecting the lead wire between the new transformer and the cable heads, in addition to constructing the detour circuit, Hitachi asked the customer to limit the output of unit No. 9, which further reduced the induced current and made the work safe.

6. Conclusions

This project to help solve the social problem of a power supply crunch was an invaluable experience for Hitachi, as it looked beyond conventional frameworks to take the best actions it could, while sharing with the customer information about the risks and opportunities of shortening processes. Hitachi made a significant contribution to power supply stabilization in Japan by rapidly restoring the unit No. 8 GSUT.

Acknowledgments

In the work on the rapid restoration of the unit No. 8 GSUT at the Nakoso Power Station of Jōban Joint Power Co., Ltd., Hitachi received the support of Jōban Joint Power Co., Ltd. and many other stakeholders. The authors would like to express their deepest gratitude to everyone involved in the project.

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EconiQ Technology Eliminating SF_6 in High-voltage Switchgear and Circuit-breakers

Significant progress has been made in recent years to decarbonize electricity generation through the increased build-out of renewable energy, such as solar and wind. However, addressing greenhouse gas emissions from the transmission and distribution portion of the energy value chain has proved to be a challenge as well. Eliminating SF_6 use in high-voltage electrical substation equipment, including circuit-breakers and gas-insulated switchgear, will be the key to achieving net-zero and enable more sustainable grid operations. SF_6 is one of the most potent greenhouse gases known to man and has a global warming potential 25,200 times higher than CO_2. When leaked, it remains in the Earth's atmosphere for 3,200 years. This article discusses how Hitachi Energy is helping to accelerate the industry's transition away from SF_6 with eco-efficient EconiQ technology.

Christian Ohler, Ph.D.
Navid MahdiZadeh, Ph.D.

1. Introduction

Electrical substation equipment is often subjected to extreme mechanical, electrical, and thermal stress during operation. This is particularly the case with high-voltage circuit-breakers and switchgear. As an example, the temperature inside a 420-kV circuit-breaker, which is typically required to interrupt fault currents of 63,000 A, can reach more than 20,000°C (approximately 36,000°F). The energy released during the interrupting process is comparable to that of a car coming to a complete stop from 100 km/h[1].

The harsh conditions demand an insulating gas with extremely high dielectric strength and interrupting capacity. Sulfur hexafluoride (SF_6) is a synthetic fluorinated compound that possesses both of these characteristics and has been prominent in electrical grids across the globe since the 1950s. In 1997, the Kyoto Protocol identified SF_6 as one of six main greenhouse gases (GHGs) that should be monitored and mitigated. Over the last two decades, significant time and financial resources have been invested by equipment manufacturers to develop more sustainable alternatives to SF_6. However, finding a solution with similar performance characteristics and comparable equipment footprint has been a challenge.

2. The Search for an SF_6 Replacement

Over the years, various alternatives to SF_6 have been developed and tested in high-voltage applications, some with more success than others. In recent years, vacuum circuit-breakers combined with synthetic air as the insulating gas have been touted as one of the leading candidates to replace SF_6. Synthetic air has a global warming potential (GWP) of zero. However, it has only modest dielectric properties. This typically leads to metal-enclosed switchgear such as gas-insulated switchgear (GIS) being larger and heavier than equipment that uses SF_6 (or other advanced alternative gas mixtures).

The size of high-voltage GIS is important for several reasons. Firstly, substations tend to be near urban centers, where available space is often limited. Secondly, if more materials and energy must be used during the manufacturing process, any carbon footprint reductions achieved by using synthetic air are offset.

Fluoronitrile (C_4-FN)-based gas mixtures have emerged as a more effective solution for high-voltage equipment, especially metal-enclosed switchgear including GIS, gas-insulated lines (GILs), dead tank breakers (DTBs) and hybrid switchgear. Pure C_4-FN has twice the dielectric strength of SF_6. When mixed with carbon dioxide (CO_2) and oxygen (O_2), its CO_2 equivalent is nearly 100 times less than SF_6. Other key advantages include:

(1) Equipment using the C_4-FN-based mixture is as compact as existing SF_6 products with identical ratings
(2) It is scalable to higher voltages
(3) It is as reliable as SF_6
(4) It delivers the lowest total carbon footprint

3. How Hitachi Energy Is Pioneering SF_6-free Technology

Hitachi Energy is a global leader in the development of sustainable switchgear solutions and has made substantial progress over the past two years to commercialize high-voltage products that utilize the new C_4-FN-based gas mixture.

In 2021, following a collaborative, cross-licensing agreement with GE Renewable Energy's Grid Solutions, Hitachi Energy launched a new line of eco-efficient, high-voltage switchgear products known as EconiQ[2]. Multiple high-voltage SF_6-free EconiQ products have already been installed across the globe, including 72.5-kV and 145-kV live tank breakers (LTBs) and 145-kV GIS, as well as 420-kV GILs and EconiQ retrofill.

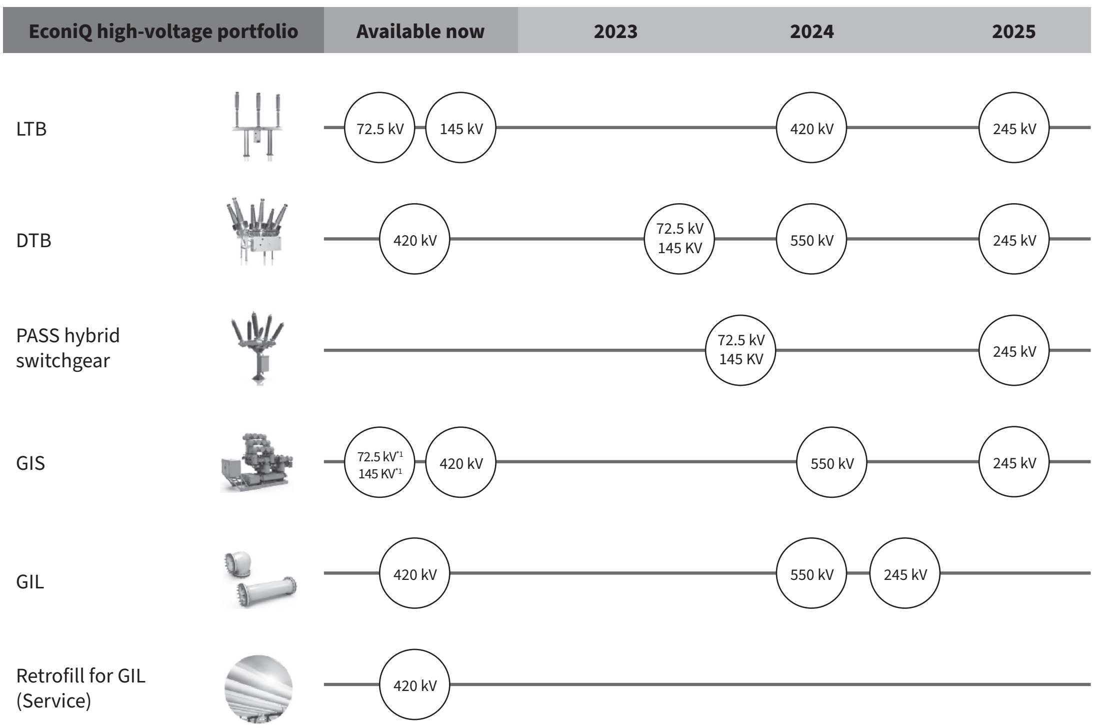
In late 2022, an important milestone was reached with the introduction of a 420-kV and 63-kA SF_6-free circuit-breaker. Circuit-breakers of this rating are particularly important for power transmission over long distances. The commercialization of an SF_6-free alternative is important, as it will unlock new decarbonization pathways for transmission system operators (TSOs). The circuit-breaker has passed all relevant tests described in the International Electrotechnical Commission (IEC) and Institute of Electrical and Electronics Engineers (IEEE) standards for 63 kA, 5000 A, 50 and 60 Hz. Its footprint is also comparable to that of SF_6-based 420-kV circuit-breakers.

Hitachi Energy's plan is to expand the SF_6-free portfolio across the entire high-voltage switchgear range in the coming years (see **Figure 1**).

4. Project References

Several installations of the EconiQ 420-kV SF_6-free circuit-breaker are slated in the coming years. Some of Hitachi Energy's recent project announcements are outlined below.

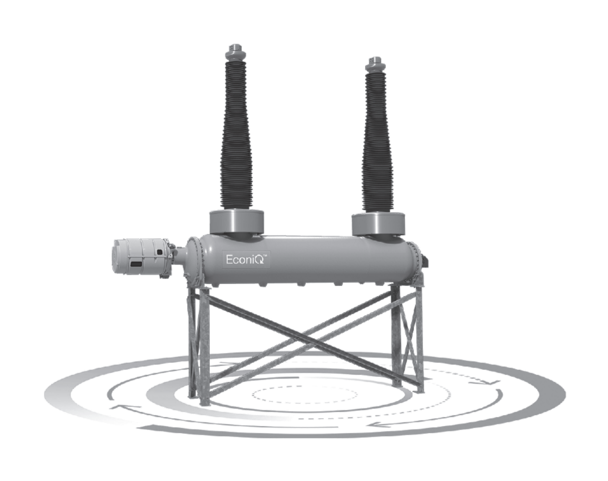
Figure 1 — EconiQ High-voltage Portfolio Roadmap
Hitachi Energy's plan is to expand the SF_6-free technology across the entire high-voltage product range in the coming years.



LTB: live tank breaker DTB: dead tank breaker PASS: plug and switch system GIS: gas-insulated switchgear GIL: gas-insulated transmission line
*1 Compact solution and 60 Hz will be available in 2023 and 2024.
*2 This roadmap contains forward-looking information based on the current best expectations, estimates, and projections. Hitachi Energy reserves the right to make changes without prior notice.
*3 Manufactured by/for a Hitachi Energy company.

Figure 2 — EconiQ 420-kV DTB

The first installation of the 420-kV SF_6-free circuit-breaker in a dead tank breaker (DTB) application will take in place in a 345-kV transmission system in the USA.



(1) USA

The first installation of the 420-kV circuit-breaker is scheduled to take place in late 2023 in the USA, where it will be used as a DTB in a 345-kV substation (see **Figure 2**). The operator of the substation, Eversource Energy, serves approximately four million customers in the Northeast region. The project will play a key role in helping Eversource drive sustainability initiatives, one of which is to achieve carbon neutrality in its operations by 2030.

(2) Germany

Another installation of the EconiQ 420-kV circuit-breaker in Germany will be the first application of the circuit-breaker in a GIS. Hitachi will install three bays of GIS at a substation on TenneT TSO GmbH's power grid. The project will allow for the avoidance of approximately 2,300 kg of SF_6, which equates to CO_2 emissions from over 1,100 passenger vehicles annually. The project's expected completion date is 2026.

(3) UK

Hitachi Energy and Linxon UK Ltd. are collaborating to strengthen London Power Tunnels, a key power infrastructure project that will ensure reliable, clean electricity supply for England's capital city. To support National Grid in accelerating its net-zero targets, Hitachi Energy will deliver EconiQ 420-kV SF_6-free GIS and GILs. As one of the world's largest investor-owned transmission and distribution utilities, National Grid has the ambition to remove all SF_6 from its fleet by 2050.

5. Conclusions

Utilities and TSOs have historically been risk-averse when it comes to the implementation of new technologies. This is not without good reason, as grid stability and availability are of the utmost importance. As penetration from renewables like wind and solar continues to increase, existing transmission and distribution infrastructure will have to be expanded and adapted. Typically, power from a wind farm travels a much further distance to the end-user when compared to a conventional generating source. As a result, there will be a growing demand for higher voltage systems and more substations. While the requirement for high reliability will remain a top priority when building out new infrastructure, the growing focus on sustainability means that GHG emissions must also be considered.

The elimination of SF_6 from high-voltage equipment is now widely accepted by both industry and governments as being an important step toward reaching net-zero. Among all alternatives, C_4-FN-based technology has proved to be the solution to replace SF_6 in high-voltage equipment. Total carbon footprint comparisons favor C_4-FN-based gas technology over the high-voltage GIS using pressurized air as the insulating medium. The technology has gained traction in recent years as large industry players across the globe, including in Europe, China, and Korea, are already using the C_4-FN-based mixture in their equipment.

Hitachi Energy's objective is to have the EconiQ technology in place across its entire high-voltage product range before the end of the decade—demonstrating the scalability of the portfolio and further strengthening the company's position as a sustainable technology leader within the industry.

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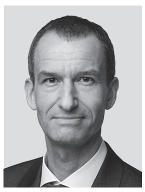

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Control and Protection for HVDC

An introduction to MACH

Recent years have seen an unprecedented growth in utility investments globally in HVDC transmission links, due to the superiority of HVDC technology in transmitting power over long distances with extremely high efficiency, controllability, and the unparalleled ability of HVDC technology to solve many of the challenges in today's complex power grids and to support the journey towards a carbon-neutral energy system. A crucial element of HVDC technology is its control and protection system—often called the brain of HVDC transmission systems. Hitachi Energy's state-of-the-art MACH control system provides unequalled calculation capacity and enables a high degree of integration and handling of all HVDC control and protection functions. MACH is a dedicated, highly performance-optimized control system key to the superior performance and reliability of HVDC and power quality solutions supplied by Hitachi Energy. This article introduces the HVDC MACH control system, its main capabilities, advantages, system architecture, and future outlook.

Hans Björklund
Daniel Hallmans
Bhagwat Gahane
Veeman Buell

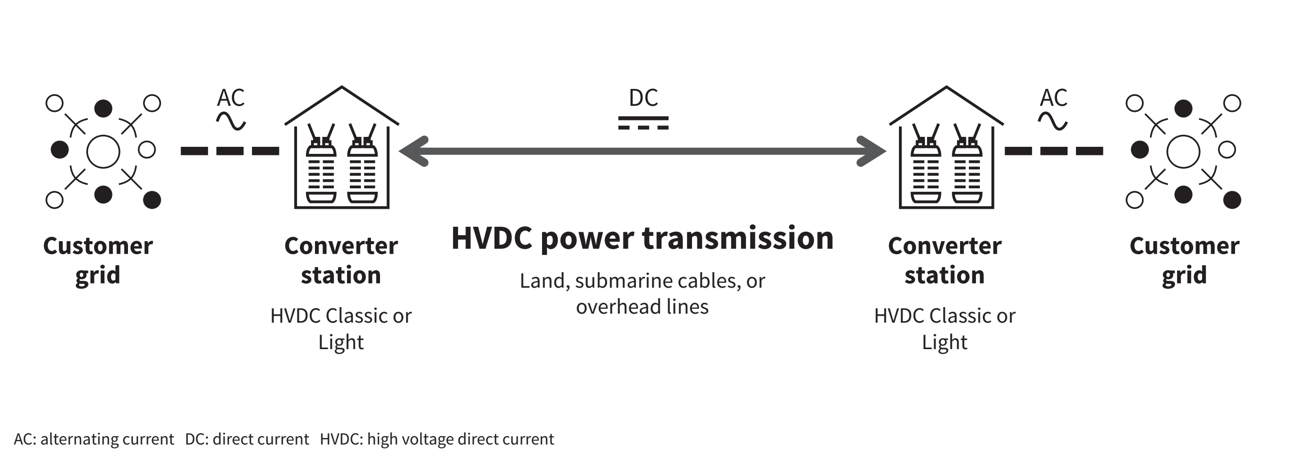
1. Introduction

High-voltage direct current (HVDC) is a key enabler for a carbon-neutral energy system. It is highly efficient for transmitting large amounts of electricity over long distances, integration of renewables, and interconnecting grids, which creates opportunities for new sustainable transmission solutions.

HVDC systems can transmit more electrical power over longer distances than similar alternating current (AC) transmission systems, which means that fewer transmission lines are needed, saving both investment and land usage. In addition to significantly lowering electrical losses, HVDC technology is easily controlled, and can stabilize and interconnect AC power networks that are otherwise incompatible (see **Figure 1**).

Today, there are two main technologies. HVDC line commutated converter (LCC), also called HVDC Classic, was the first developed technology. LCC is used primarily for connecting remote generation over long distances, grid interconnection, and direct current (DC) links in AC grids, overland or subsea, where conventional AC methods cannot be used. The second technology is the HVDC voltage source converter (VSC), developed by Hitachi Energy and launched in 1997 as HVDC Light. It is an adaptation of HVDC Classic used to transmit electricity in using environmentally friendly cables, overhead lines, or a mix of cables and overhead lines. It can be used for connecting remote generation, grid interconnections, offshore wind connections, DC links in AC grids, power from shore, city center infeed, and connecting remote loads. With Hitachi Energy HVDC Classic and HVDC Light, it is possible to transmit power in both directions and support existing AC grids in order to increase robustness, stability, and controllability.

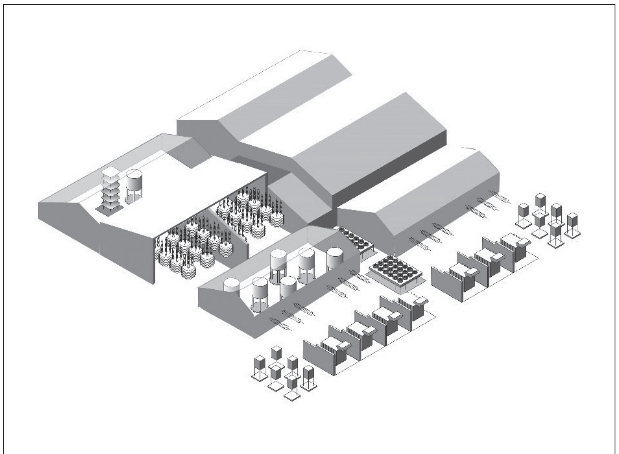
Figure 1 — Illustration of HVDC Transmission System
An HVDC transmission system interconnects two customer grids, which can be asynchronous or even have different frequencies.



2. Introduction to HVDC Control and Protection

An HVDC station is a complex installation containing many parts that need to be carefully controlled to guarantee the best performance of the complete system. An often-used configuration is called a bipole, which consists of two poles, one with positive and one with negative polarity. One pole consists of converter valves and phase reactors located indoors and power transformers located outside (see **Figure 2**). There are also many other high-voltage electrical power devices such as breakers, disconnectors, current transformers, capacitive voltage dividers as well as very specialized measurement devices like optically powered direct current measurement units and compensated resistive voltage dividers. The converter valves need a cooling system using deionized water to cool the power electronic switching components and an extensive auxiliary power system to keep the station running.

Figure 2 — Illustration of a Typical HVDC Bi-pole Installation
The HVDC AC converter station in bi-pole configuration has two parallel HVDC converters consisting of transformers, cooling system, reactors, HVDC valve halls and other AC transmission equipment. Each electrode can be operated individually, allowing power transmission to continue even during maintenance.



HVDC converters are controlled by providing signals to operate the converter valve semiconductors. These components react in just a few micro-seconds, meaning that an HVDC converter represents a uniquely controllable device in a power system. With a meticulously designed control system, such fast power changes can be used to stabilize connected AC power systems in many different ways, for example, by damping power oscillations, providing support for sudden loss of power generation, and balancing voltage-changes using reactive power control.

As an HVDC converter cannot operate without a working control, that system must also be very reliable. To achieve such high degrees of reliability, a 100 percent digitalized control system, with extremely fast switchover to a hot standby system with no interruptions in power transfer, was introduced by Hitachi Energy in 1982. This configuration has since then been used for all Hitachi Energy HVDC installations.

With such fast-reacting converters and control systems, it follows that the protections must also be much faster than traditional AC protections and must have reaction times well below 1 millisecond to avoid damage to the converter valves. The building blocks of the modular advanced control for the HVDC (MACH) system are equally well suited to building a fully duplicated centralized protection system, connected to measurement devices using very fast optical process buses.

The high performance of the MACH system has also allowed for high integration of other important functions such as fully duplicated and integrated transient fault recorders that generate easily readable records in standard IEEE common format for transient data exchange (COMTRADE) format. As a fully integrated application it can record any signal available in the computers or digital signal processors (DSPs), and the number of recordable signals is only limited by available memory.

Additional high-speed global positioning system (GPS) clock-synchronized analog inputs (50 MHz) have been added to allow integration of line and cable fault locators that use travelling waves technology and accurately determine the fault locations in case of DC line or cable fault.

3. MACH Control Platform

The MACH control and protection system can be divided into several different building blocks (see **Figure 3**), that together create a modular system that can control all types and generations of HVDC systems that have been delivered by Hitachi Energy or even other HVDC vendors. With this backward compatibility, Hitachi Energy is able to support its customers with at least one control and protection upgrade during the expected 40-to-50-year lifetime of an HVDC installation benefitting from the latest advances in control and protection technology.

The main closed loop control consists of four different parts that all are redundant, the main computer system consisting of three different products: the PS700, a high-performance server type computer with 8–12 cores, the PS935, an 8-core DSP platform, and the PS775 redundancy changeover unit (see **Figure 4**). The main controller receives its input from the input/output (I/O) system through different process buses. Depending on the system need, either dedicated I/O systems are used (for example, low-latency I/O at 500 k samples per second or unconventional measuring units, such as, digital optical instrument transformers) or standard conventional I/O systems over IEC61850 (used for control of larger substations connected to the HVDC system). A core part of the system is the converter valve electronics that connects directly to the semiconductors that are in each position of the converter valve. The valve control unit acts as an interface between the hundreds or thousands of positions in the converter valves and main control system. Together, the four different building blocks form control and protection loops ranging from tens of microseconds to milliseconds.

All application codes are programmed by a common graphical programming language, developed and owned by Hitachi Energy, called HiDraw, which allows for design, real-time debugging, and simulations of complete converter systems before they are built, connected to power systems models. HiDraw has been the programming language for MACH for the past 30 years and allows for exceptionally fast upgrades of older installed systems since, for example, control loops and protection schemes can be directly reused and integrated with the latest base designs.

Connected to the station level bus there are several different systems, including operator workstations, servers, and gateways interacting with third party systems. Additionally, the Hitachi Energy energy connect (EC) edge gateway enables MACH to interact with a Hitachi Energy Lumada/IdentiQ system.

Figure 3 — Simplified Hierarchical Overview of MACH Building Blocks and Interfacing Systems

MACH includes a variety of hardware modules to monitor, control, and protect the HVDC systems.

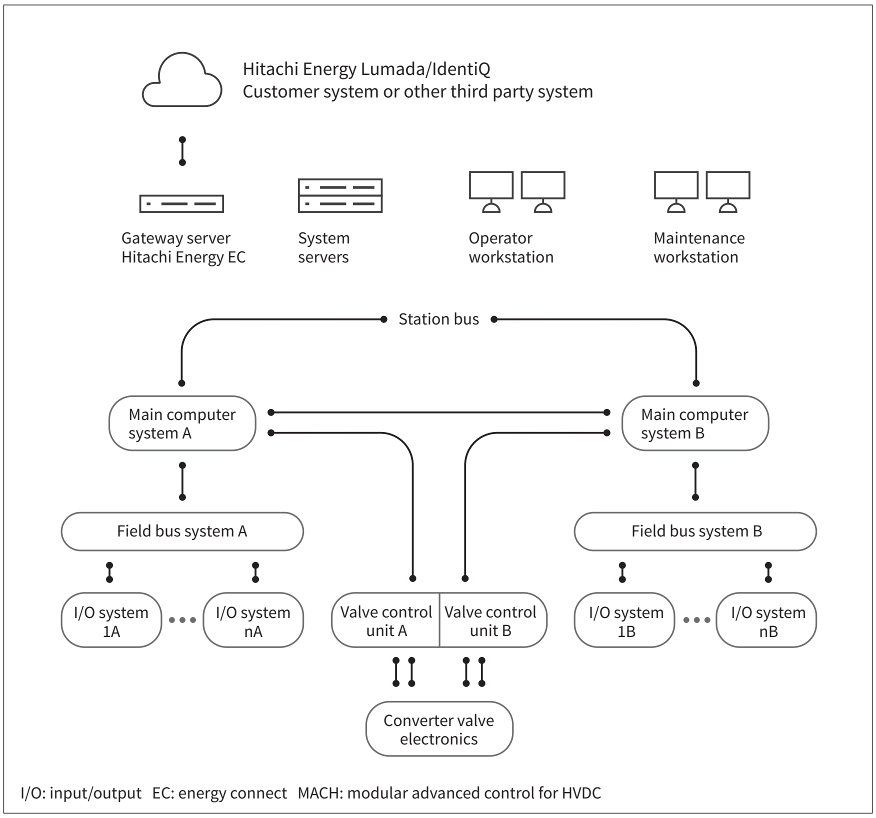
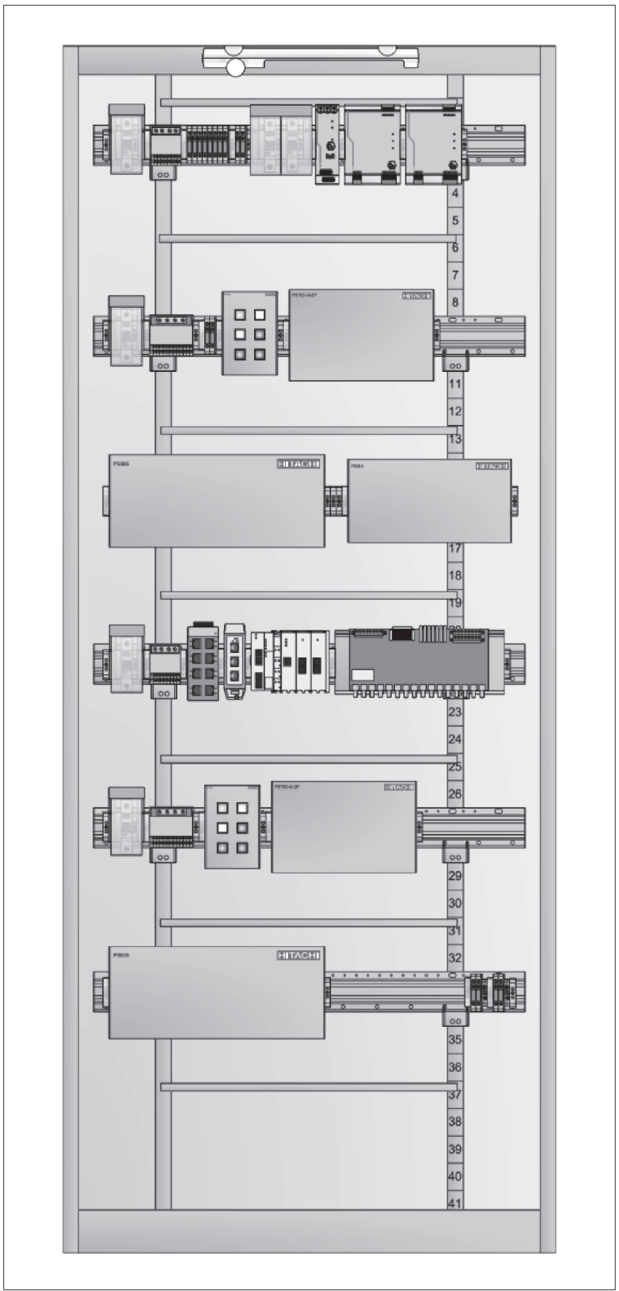


Figure 4 — A typical Control and Protection Cubicle
The upper section is used for control and the lower section for protection.



4. Other applications

The superior performance and converter control capability of MACH makes it suitable for other applications within Hitachi Energy that need similar performance. These include power quality systems such as static var compensators (SVCs), static synchronous compensators (SVC Light STATCOMs) and series compensators, used to provide more power and control in existing or new AC networks. The MACH system is also being extended to energy storage solutions like the E-STATCOM (SVC Light Enhanced) as well as low- and medium-voltage converter applications such as EV chargers and static frequency converters.

Hitachi Energy's MACH digital control platform is a core technology piece in the energy transition, transmitting large amounts of power over long distances with extremely high efficiency and integrating renewable generation at scale into the grid. It is what supports the reliable, resilient, and flexible power grid that is needed to meet the world's growing electricity demands and maintain the momentum toward net zero emissions.

5. Conclusions

The MACH system architecture plus hardware and software interfaces have been carefully chosen so that MACH can continue to evolve and remain the base control and protection system for Hitachi Energy's future HVDC and power quality solutions, thereby enabling the energy transition.

The company expects to introduce even higher performance, more integrated solutions, and new innovations, without changing the basic structure of MACH. Interoperability will be an increasingly important part of future systems, enabling, for example, DC-grids where interaction between several HVDC stations from different manufacturers will be required, in addition to new system technologies such as hybrid HVDC breakers.

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FEATURED ARTICLES

Energy Solutions for GX

Amid increasing global action on making a green transformation (GX) to a sustainable society, renewable energy has come to be recognized as playing a key role in achieving decarbonization and breaking the reliance on fossil fuels. Unfortunately, numerous challenges need to be overcome if a reliable supply of electric power is to be achieved using the fluctuating output of this weather-dependent form of generation.
These featured articles present Hitachi initiatives to support the adoption and expansion of renewable energy, both to achieve decarbonization and to add value for consumers. Along with wind power generation solutions and managed services that support companies in their efforts to achieve carbon neutrality, the efforts also include technologies for efficient grid operation, covering electricity distribution, the coordinated operation of distributed generation equipment, and battery energy storage systems (BESSs).

Support for Carbon Neutrality through GX, DX, and Managed Services

Corporate management has been called on over recent years to address a variety of challenges, notably decarbonization, rising energy prices, and a shrinking workforce. To address these challenges, Hitachi has been making progress on support for carbon neutrality measures along with utilizing its Lumada models to facilitate a transformation in the business processes associated with energy and facilities. It has also sought to help companies strengthen their core businesses by offering managed services that make the operation, maintenance, and asset management of energy-related equipment less burdensome. This article presents existing examples and future prospects for measures that help to enhance corporate value by taking on tasks that support customers' core businesses, such as more sophisticated equipment management, in addition to the utilization of Lumada models to enable smarter energy use across multiple sites or areas.

Koji Hataya
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Kento Takekoshi
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1. Introduction

The diverse challenges that confront today's corporate management can be broadly divided into the following three categories.

(1) Economic challenges

Uncertainty over energy costs caused by geopolitical risk is having a major impact on both operations and profitability.

(2) Environmental challenges

Having become an issue that no business can ignore, carbon neutrality now needs to be addressed as a business risk rather than in terms of advantage or disadvantage.

(3) Societal challenges

Shortages of maintenance workers and constraints on investment mean that little progress is being made on efficiency improvements or other upgrades to energy infrastructure constructed since Japan's bubble era of the 1980s.

However, as efforts that address these challenges on an ad hoc basis will find it difficult to resolve them in any fundamental or sustained manner, what is needed are enablers[*1] that can provide comprehensive and ongoing solutions and support.

2. Measures for Carbon Neutrality that Enhance Corporate Value for Customers

When embarking on work toward carbon neutrality, Hitachi first puts together a "to be" vision of what it wants to achieve so as to provide a clear indication of the direction and strategy, and also a portfolio and roadmap for doing so. Once agreement is reached with the customer, this is then used in subsequent progress monitoring. As this work proceeds over long periods of time, ongoing support is delivered using Lumada models.

*1 In a business context, enablers serve in roles that provide backup support, functioning as part of the core infrastructure essential for the business growth of other companies.

2. 1 Solution Building Blocks for "Hitachi Carbon Neutrality 2030"

Portfolio design (consulting) categorizes measures for achieving carbon neutrality into "reduction," "generation and procurement," and "offsets," setting targets based on the relative proportion of measures from each of these three categories.

To make this process work more effectively, Hitachi determines which model best fits a customer based on their energy use characteristics. To support rapid and flexible delivery, it treats the different solutions for achieving carbon neutrality as building blocks that can be combined as needed (see **Figure 1**).

The following are examples of how this use of solution building blocks might work.

(1) Reduction: A microgrid service for energy supply that combines digital transformation (DX) and green transformation (GX)

An example of how reduction can form part of a portfolio is a microgrid service for energy supply that combines DX and GX. The service is scheduled to commence operation in the latter half of 2023 at four adjacent Hitachi facilities in Hitachi City, Ibaraki Prefecture. Electricity generated by gas cogeneration is used at the four sites and the waste heat from generation is used for clean room air conditioning. As coordinating operation across the entire area allows for more efficient energy use than would be possible if each site operated independently, it is anticipated that this will reduce total carbon dioxide (CO_2) emissions across the four sites by 15%, equating to 4,500 t[*2] annually. The service works with a cross-industry consortium that includes energy and finance companies, making equipment operation, maintenance, and asset management easier by enabling the sites (consumers) to shift from an ownership-based to a usage-based model for their energy infrastructure. Future plans include the use of DX to further improve energy infrastructure and its operation.

(2) Generation: Multi-site energy management utilizing renewable energy generation and the "self-consignment" of electric power

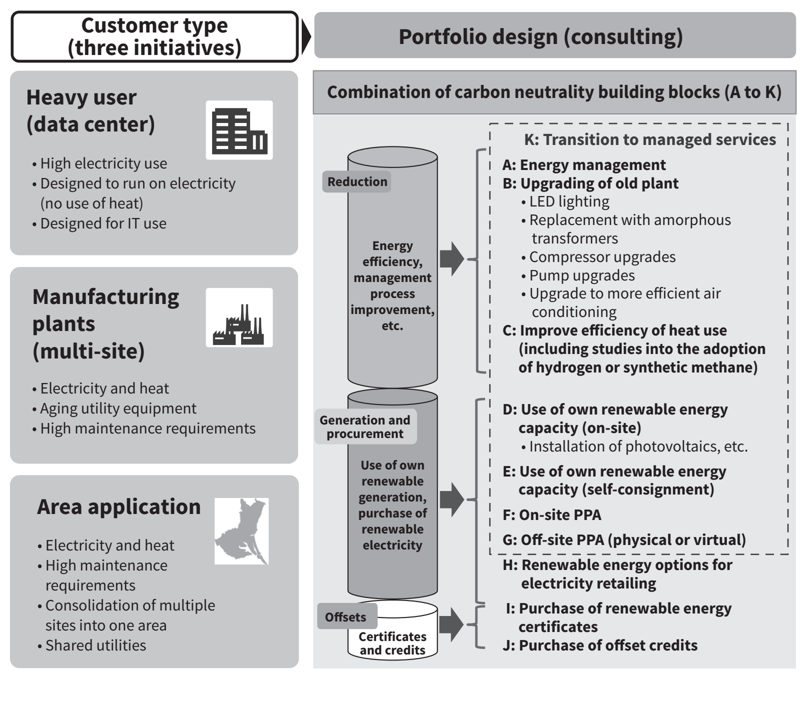
While photovoltaics are commonly used as a means of adding a generation component to a portfolio, this generation in many cases will not be located at the site where the power is to be consumed. For such customers, Hitachi has started working on how to combine resources such as renewable energy, grid monitoring and control systems, and artificial intelligence (AI) to enable customers with multiple sites to take advantage of self-consignment (delivery via the grid of electric power generated by their own remotely located plant) in their energy management.

As a pilot model, Hitachi is planning to commission a system in March 2024 that will utilize electric power generated by a photovoltaic power plant located at Hitachi's research and development facility in Hatoyama City (Saitama Prefecture). Any excess power not required by the Hatoyama facility is supplied by the system to a similar

*2 According to Hitachi Ltd.'s estimate

Figure 1 — Portfolio Design

Portfolio design combines different solution building blocks based on what fits best with the customer's energy usage characteristics.



LED: light-emitting diode PPA: power purchase agreement facility in Kokubunji, Tokyo. The goal is to reduce CO_2 emissions at Kokubunji by a net 75% relative to FY2010 by FY2030[(1), *3].

By making use of energy across multiple sites based on their individual energy circumstances, this approach enables optimization across sites with different electricity use characteristics and amounts of space available for equipment installation. Furthermore, to achieve carbon neutrality in ways that would be difficult for individual sites acting alone, future plans include the sharing of electric power across a number of sites by using N:M configurations in which multiple generation sites supply multiple consumers.

3. Microgrid System for Local Sourcing of Energy

Following the 2020 announcement by the Japanese government of its 2050 Carbon Neutral Declaration, an increasing number of local government agencies around Japan have been making their own zero-carbon declarations.

It was against this background that Hitachi Power Solutions Co., Ltd. signed a memorandum of understanding on October 11, 2022 with Okuma Town in the Futaba District of Fukushima Prefecture for a project to build the Shimonogami smart community, Okuma having previously announced a zero-carbon declaration in February 2020.

The project includes plans to install a megawatt-class solar power plant, a battery energy storage system, its own transmission lines for delivering electric power to users, and a grid control system that provides optimal control of the overall network. By supplying electricity derived from renewable energy to the Shimonogami area around Ono Station in Okuma, it will support the establishment of a system for the local sourcing of energy.

The project will help Okuma in its goal of becoming a zero-carbon town through the use of locally generated renewable energy (see **Figure 2**).

*3 Combined reductions including the installation of energy-efficient equipment and other measures for reducing CO_2.

4. Energy Transformation to Carbon Neutrality

4. 1 Trends in Hydrogen and Methanation and Hitachi's Work in This Field

Along with an increased proportion of energy coming from renewable sources, serious attention is being given in Japan and elsewhere to the adoption of power-to-gas (P2G) as part of the transition to a carbon-neutral society in 2050. This involves the use of excess renewable electric power to produce hydrogen. At companies, industrial complexes, and ports, a lot of work is currently going into the development of supply chains for the production, transportation, storage, and use of hydrogen, with the participants working together in ways that take advantage of their respective corporate strengths and local circumstances.

Hitachi is directing its efforts toward the production and use of hydrogen and synthetic methane in particular. To enable low-cost hydrogen production and build a hydrogen value chain, engineering work is focusing on high-voltage electrolyzers and hydrogen distribution control as well as on providing a hydrogen dual-fuel option for gas turbines and gas engines. As one way of using hydrogen is in the form of synthetic methane, Hitachi is helping Japan's gas industry achieve its goal of 1% synthetic methane by 2030 and 90% by 2050, focusing on biomethanation and conducting studies aimed at commercialization. As well as supplying the key products for hydrogen and synthetic methane that serve as the heart of the overall P2G system, Hitachi is also looking to supply operational technology (OT) and IT for asset life cycle management, supply chain management, and the trading of carbon credits (see **Figure 3**).

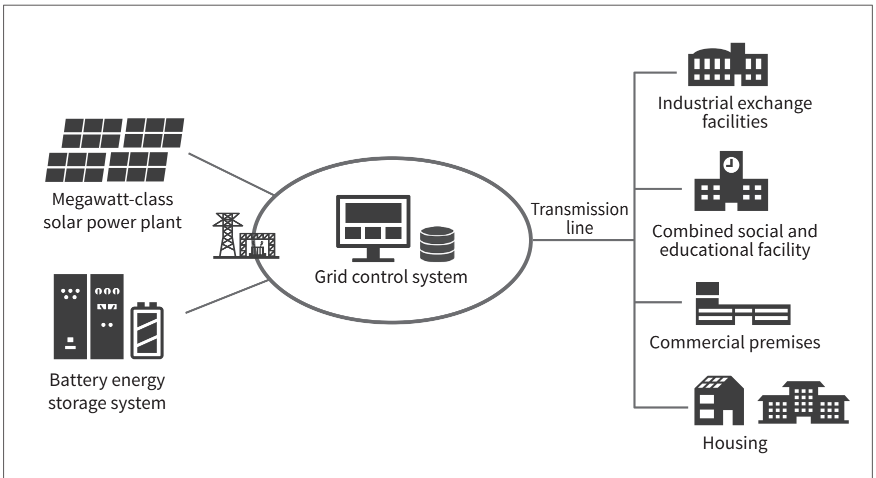
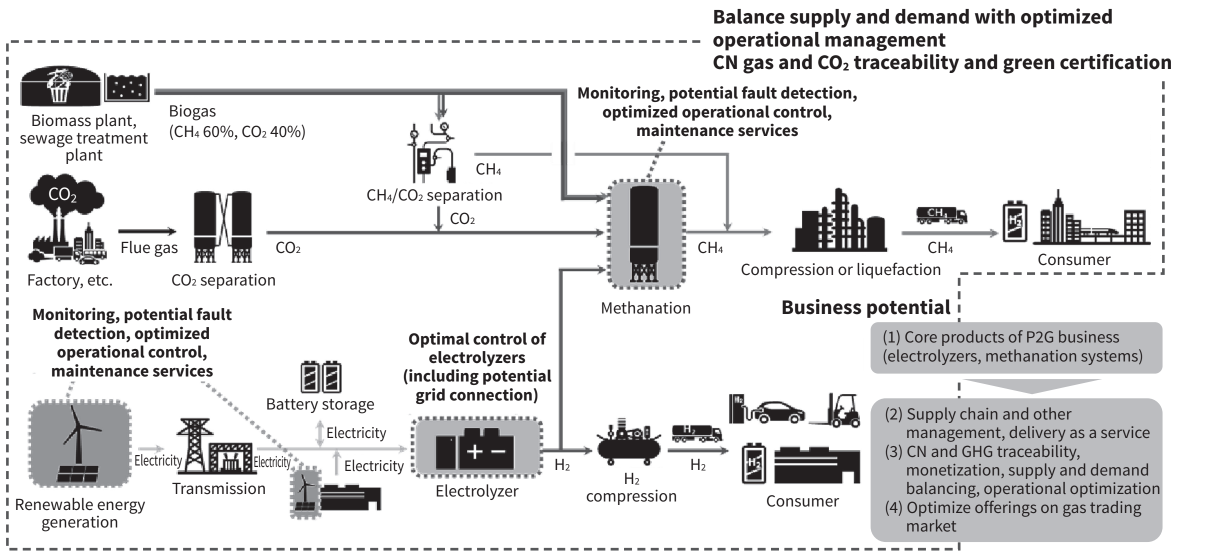


Figure 2 — Diagram of Shimonogami Smart Community Project Planned for Okuma Town, Futaba District, Fukushima Prefecture

The project will use its own transmission lines to supply renewable energy generated by a megawatt-class solar power plant to consumers in the Shimonogami area around Ono Station in Okuma. Featuring a grid control system and battery energy storage, it will support the establishment of a system for the local sourcing of energy.

Figure 3 — P2G System for Hydrogen and Synthetic Methane

The system can supply either synthetic methane or hydrogen by combining methanation with the use of excess renewable energy to power the production of hydrogen by an electrolyzer. Demand information is used for optimal system-wide energy management.



P2G: power-to-gas CN: carbon-neutral GHG: greenhouse gas CH_4: methane CO_2: carbon dioxide H_2: hydrogen

4. 2 Trial Use of Hydrogen for Carbon-neutral Heat

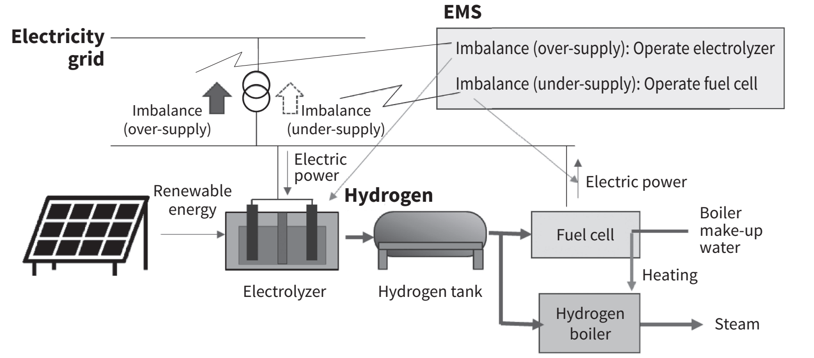
The bulk of corporate CO_2 emissions can be divided into those associated with electricity and those associated with heat. In other words, carbon neutrality needs to address not only the electricity-related CO_2 emissions that can be reduced through measures such as renewable generation, but also emissions associated with the supply of heat. This section describes a project in which hydrogen was used to supply carbon-neutral heat.

The project involves a corporate group that is undertaking trials with assistance from the Ministry of the Environment FY2022 Subsidy for CO_2 Emission Control Measures. As 50% of their CO_2 emissions are attributable to electricity and the other 50% to heat, carbon neutrality cannot be achieved without also addressing the latter. Accordingly, the group decided to trial the use of hydrogen to supply carbon-neutral heat on the assumption that adequate supplies would be available in the future. To achieve high operational efficiency, the project involves setting up a cogeneration system in which green hydrogen produced from renewable energy is supplied to a hydrogen boiler and fuel cell. The project also plans to trial control practices based on an energy management system (EMS) that balances supply and demand by using an electrolyzer as a sink for electric power and a fuel cell as a source (see **Figure 4**).

By keeping imbalances in electric power to a minimum using the fuel cell and electrolyzer in tandem with generation equipment that is to be installed by Hitachi in the future, the goal is not only to achieve carbon neutrality in the supply of heat, but also to make the electricity supply more reliable. Hitachi has served as a long-term energy

Figure 4 — Block Diagram of System for Carbon-neutral Supply of Heat

The electrolyzer runs on electricity generated by photovoltaic panels and the hydrogen it produces is stored in tanks. By supplying the stored hydrogen to either a hydrogen boiler or a fuel cell, depending on whether there is an under- or over-supply of electric power, the system makes the power supply more reliable while also achieving carbon neutrality in the supply of heat.



EMS: energy management system

partner for the group, including by helping them to develop a roadmap for carbon neutrality and assisting with equipment installation. Hitachi also plans to utilize the know-how it has developed on this project in co-creation with other companies that have made a commitment to carbon neutrality.

5. Process Improvement and Managed Services

Along with the use of digital technology for continuous monitoring, action on carbon neutrality also calls for ongoing progress accompanied by repeated analysis and testing. Because data appreciates (grows in value) over time whereas equipment depreciates (deteriorates), this gives rise to improvements in process (operations and maintenance).

5. 1 Managed Services for Equipment Management

This section describes a solution for transforming equipment management that was supplied to a food retailer. The challenges that the company faced with regard to equipment operation were: (1) how to deal with the complexity of maintenance work while keeping costs low, and (2) how to make progress on carbon neutrality.

In response, Hitachi offered a package that combined the following two systems.

(1) Equipment management system

A single point of contact was established for equipment maintenance and more sophisticated equipment management practices were adopted in which Hitachi was responsible for all steps from data entry to management.

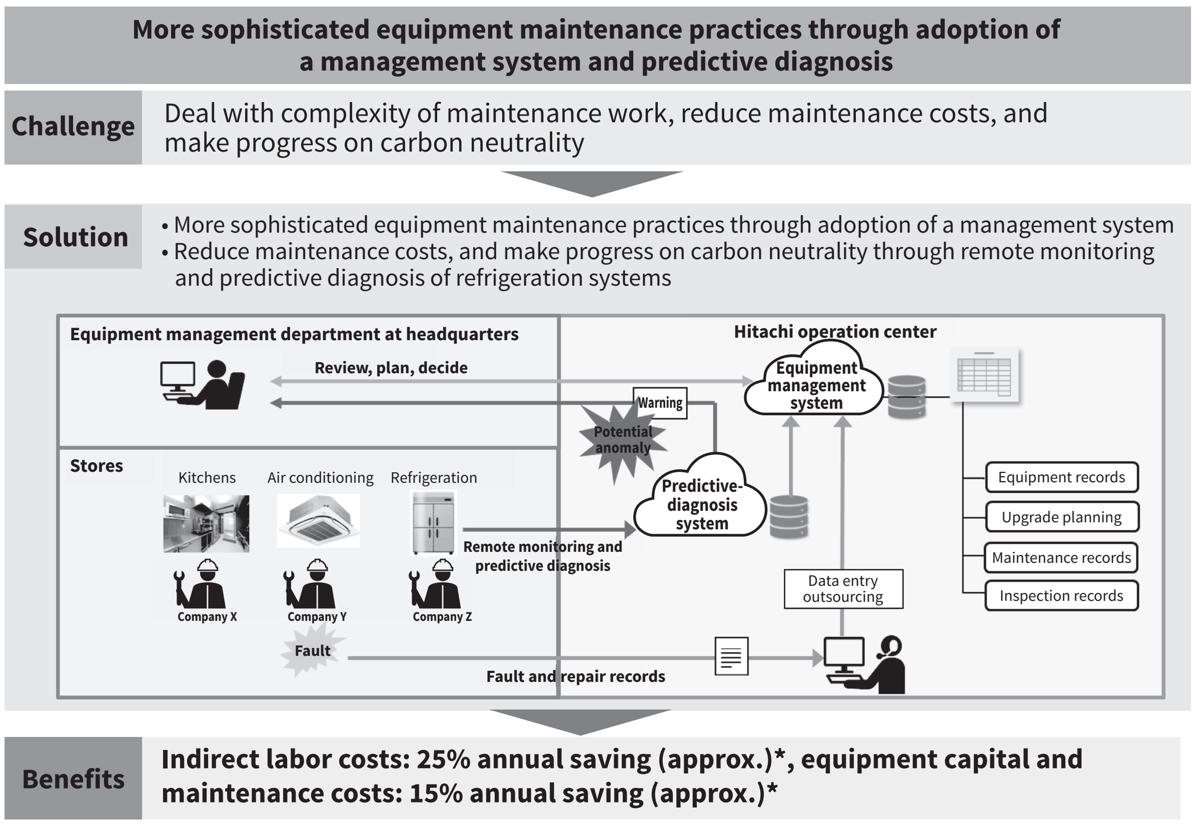
(2) Predictive-diagnosis system

Through the remote monitoring and predictive diagnosis of energy and operating conditions for chiller and freezer systems, this system reduces food wastage while at the same time cutting maintenance costs through preventive maintenance. It provides ways to deal with the impacts that unexpected faults in this equipment have on retail operations and promotes carbon neutrality by the early detection of refrigerant leaks.

After an initial rollout to 10 stores, the plan is to expand the predictive diagnosis system to cover all 100 stores while also making use of data on the managed services for energy and facilities. In practice, this will include putting data to practical use in areas like vendor selection and store design

Figure 5 — Provision of Managed Services for Equipment Management to Retailer

The figure illustrates the operational issues facing the food retailer, the solutions provided, and the benefits it has delivered. The solution took the form of an equipment management system and a predictive-diagnosis system combined as a single package.



* The benefits are based on a simulation conducted by Hitachi, Ltd.

by taking account of statistical trends in predictive detection and operational data as well as in faults. Data will also be used for the development of optimal equipment upgrade plans and in investment decision-making.

By combining carbon neutrality with more sophisticated equipment management, this will resolve the customer's societal and environmental challenges while also extracting new value from data (see **Figure 5**).

Furthermore, by adopting consistent practices across different sites, it is anticipated that the service will deliver new benefits to the company as a whole by establishing not only an Internet of Things (IoT), such as equipment management systems, but also resource platforms for things like spare parts and maintenance staff. Beyond that, there is also scope for greater shared benefits by deploying resource platforms that transcend the borders between companies to encompass multiple sites, including those of other customers.

6. Conclusions

As the business environment in which companies operate becomes increasingly difficult, requiring that the investment of resources be focused on strengthening core operations, the time has come to reassess whether it is a good idea to continue keeping operations that support the core business (energy equipment and management) in-house, including measures for achieving carbon neutrality.

Hitachi's goal is to contribute to the core business activities of its customers by enabling them to make the change from an ownership-based to a usage-based model by outsourcing these tasks on a comprehensive and ongoing basis.

By combining GX (including green electricity generation and energy efficiency) and DX (including energy management, asset management, and the IoT), Hitachi also aims to enhance the corporate value of customers.

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One-stop Wind Power Generation Solution Encompassing Business Development and Planning to O&M

The problems posed by climate change have worsened globally over recent years, including natural disasters and the impact on ecosystems. This has led nations everywhere to accelerate their efforts to decarbonize, resulting in a rapid expansion in the installation of wind power generation capacity, one of the more effective means of doing so. Hitachi Power Solutions Co., Ltd. has since 1996 been operating its wind power business in partnership with the German wind turbine manufacturer Enercon GmbH and it has gained a large share of the Japanese domestic market for these systems. A feature of this business is that, by drawing on skills and expertise built up over many years, it can provide a one-stop service for its customers that extends from the earliest stages of a project to its completion. This article describes this one-stop service and presents examples of solutions based on wind power generation systems.

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1. Introduction

The problems posed by climate change have worsened globally over recent years, including natural disasters and the impact on ecosystems. This has led nations everywhere to accelerate their efforts to decarbonize, resulting in a rapid expansion in the installation of wind power generation capacity, one of the more effective means of doing so. Japan, too, is expected to see the ongoing installation of wind power generation, with the Sixth Strategic Energy Plan published in 2021 projecting an increase in onshore wind generation from the current 4.2 GW to 15.9 GW in 2030 (assuming strengthened policy measures)[1].

The cumulative total of wind generation system orders for Japan received by the Hitachi Group as of the end of December 2022 was 876 units, giving it a leading share of the domestic market. In particular, Hitachi Power Solutions Co., Ltd. has since 1996 been operating its wind power business in partnership with the German wind turbine manufacturer Enercon GmbH and has installed a total of 481 turbines as of March 2023.

The key feature of the wind power business of Hitachi Power Solutions is that it can support the operations of customers planning to install wind power generation across every step of the process, from the earliest stages of a project to construction, operation, and ultimately demolition. This takes the form of a one-stop service for the activities that are essential to a generation business: (1) identification and selection of sites for turbine installation, (2) business planning, including where to position turbines to get the best return, financing, and the acquisition of wind farm certification, (3) transportation and erection of generation equipment, (4) operational management to maintain and improve utilization post-commissioning, (5) maintenance to ensure equipment reliability, and (6) demolition and replacement.

2. Characteristics of each Process

This section describes each of the processes handled by Hitachi Power Solutions' one-stop service.

2. 1
Site Selection and Business Planning

For onshore wind power generation, the site selection and business planning process extends from surveying potential sites and wind conditions to basic design, detailed design, and technical review[2].

The site selection stage that covers the steps from site survey to basic design involves surveying the site conditions (surrounding topology, presence of endangered species, and so on), identification of sites with favorable wind conditions, wind condition surveys, and surveys of social factors (distance from residences, gaining of consent for noise and impact on scenery, grid connection, and transportation routes).

Past practice when identifying sites with favorable wind conditions has been to make use of resources such as publicly available maps of wind conditions[3]. To provide even better maps for site selection, Hitachi Power Solutions has developed its own proprietary wind maps in partnership with Hitachi, Ltd. using a data assimilation technique that combines atmospheric simulations with actual data collected from wind sensors located around Japan[4].

Business planning covers the detailed design and technical review. Site and geotechnical surveys are conducted based on the size of the proposed wind farm and used to assess the profitability of the project. This includes a detailed design that draws on a survey of wind conditions at the candidate site over a period of at least one year. The locations and total number of turbines are determined so as to increase total generation capacity, utilizing the results of the wind survey and wind conditions simulation to take account of the topology where the turbines are to be located and any disturbance caused by one turbine to another (see **Figure 1**).

As approximately 70% of Japan's land area is mountainous, wind farms are significantly impacted by the turbulence characteristics of such terrain as well as by typhoons and other seasonal wind conditions. Accordingly, a conformance assessment is conducted based on the strength of the selected wind turbines and the likely wind conditions at the proposed site. This is then used to support the acquisition of wind farm certification.

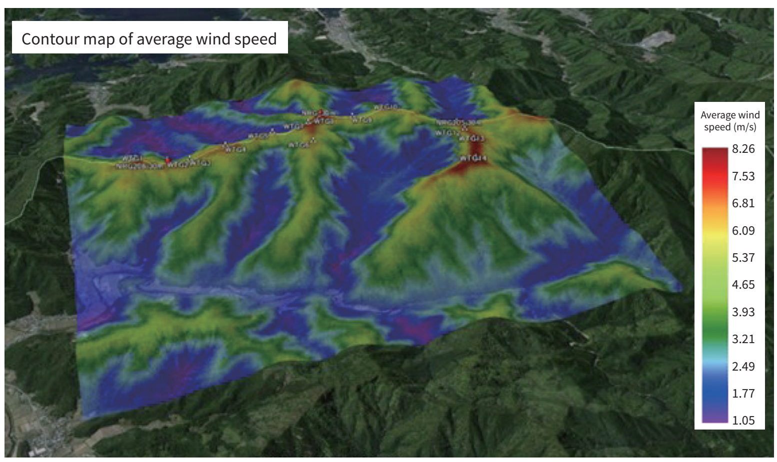
Establishing working arrangements with local government and with local businesses is extremely important when installing wind power generation. To this end, Hitachi is taking steps to further strengthen the support it offers, predicating this on active involvement by local government and business through project structures that contribute to regional revitalization and are based on co-creation with the community. This extends from financing and engineering, procurement, and construction (EPC) to operation and maintenance (O&M) and the running of the business.

2. 2
Product Lineup, Transportation, and Construction

The size of wind turbines is growing as the technology advances and customers pursue higher generation efficiency (see **Figure 2**). Turbines supplied by Hitachi Power Solutions in the past have included the E-40 (40-m rotor diameter and 600-kW rated output) and E-70 (70-m rotor diameter and 2,300-kW rated output). Subsequently, the E-82 (82-m rotor diameter and 2,300-kW rated output) became the mainstream model from about 2009 onwards amid a trend toward turbines with larger diameters and higher outputs despite wind power generation being limited to flat sites with good wind conditions and sites located

Figure 1 — Results of Wind Condition Simulation

The color-coding indicates the wind speed distribution obtained by simulation. This information can serve as a basis for deciding where and how many turbines to install.



Source: Google Earth*

* Google Earth is a trademark or registered trademark of Google LLC.

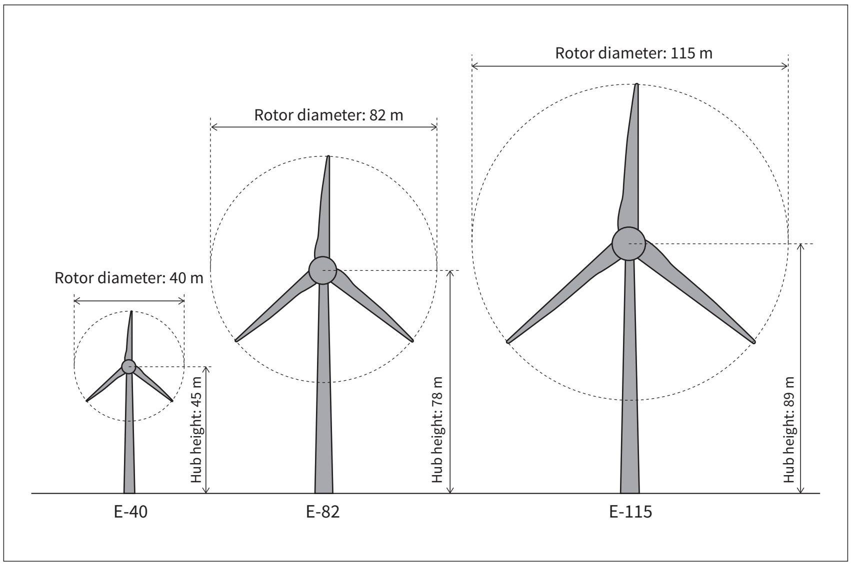


Figure 2 — E-40, E-82, and E-115 Turbines
The figure shows the E-40 turbine with a 40-m rotor, the E-82 turbine with an 82-m rotor, and the E-115 turbine with a 115-m rotor. Generation efficiency increases with rotor diameter.

from the coast to inland. With the reduction in feed-in tariff (FIT) rates and the transition to the feed-in premium (FIP) system, Hitachi went on to launch the E-115 (115-m rotor diameter and 4,200-kW rated output) turbine featuring higher generation efficiency. The first E-115 commenced operation in April 2023 at Oga City in Akita Prefecture. The next-generation model currently under development is the E-138 (138-m rotor diameter and 4,200-kW rated output), which features even higher generation efficiency. Meanwhile, Hitachi has the advantage of being able to offer a 2,000-kW-class turbine like the E-82 when this better suits the topology and other site conditions. Hitachi also intends to contribute to maintaining and expanding wind generation capacity in Japan by offering the most suitable configurations and number of units for customers whose wind turbines are coming up for replacement.

The growth in wind turbine size and blade length poses challenges for the transportation of parts. The Eurus Kamikatsu-Kamiyama Wind Farm of Eurus Kamikatsu-Kamiyama Wind Energy Corporation that commenced operation in July 2022 is situated across a mountainous region at elevations of 1,000 m or more, making transportation across steep and narrow terrain unavoidable. Along with widening the mountain roads, this difficulty was overcome by using a special-purpose blade lifter that transports the blades at a tilted angle, allowing construction to be completed successfully in areas that would have been difficult to access using conventional transportation (see **Figure 3**). The knowledge gained from this project will be put to use in the future transportation of large turbines.

2. 3 O&M

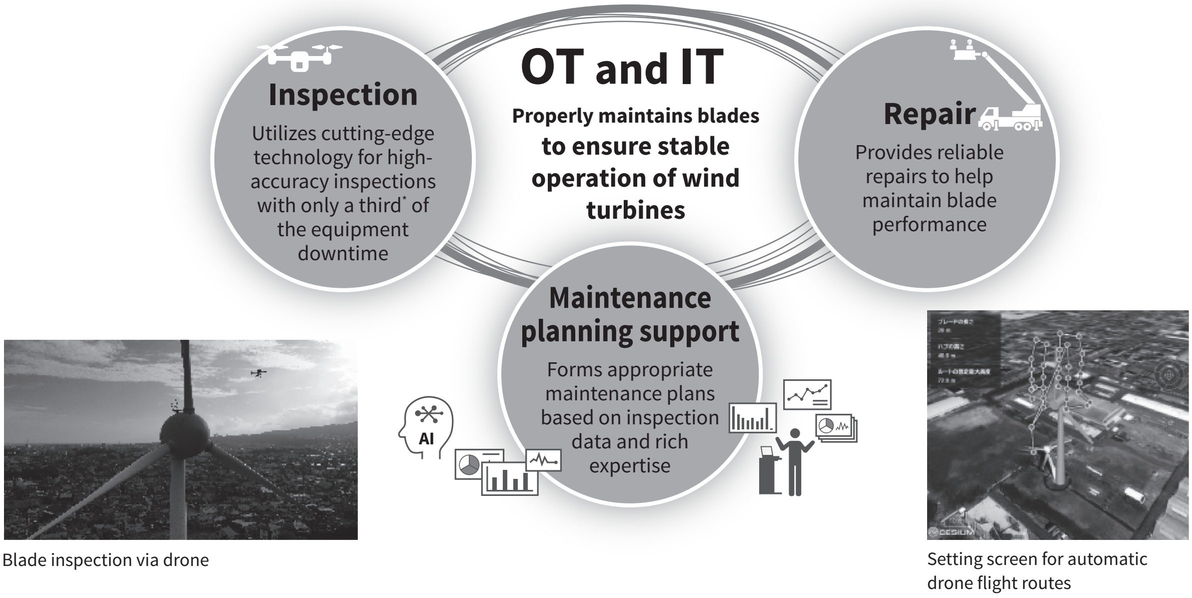
By leveraging a combination of digital technology and expertise derived from its extensive industry experience, Hitachi Power Solutions is able to operate and maintain wind power generation systems in ways that meet the diverse needs of customers.

In April 2022, it launched a total service for turbine blades that provides enhanced equipment and operational safety[5]. This operates as a one-stop service for blade inspection using drones and artificial intelligence (AI), maintenance planning, and repair of damage or wear and tear (see **Figure 4**). Benefits include reducing the amount of equipment downtime required for inspection to about one-third of previous levels. This improves profitability as less time lost to shutdowns means more time generating electric power for sale. The service is supplied as one of the solutions available on Hitachi's Lumada digital platform. Further improvements in accuracy are also planned by collecting data on how turbine blades change over time and by making use of more advanced AI.

Figure 3 — Blade Lifter in Action Transporting Blade
The range of sites that can be accessed has been expanded by using a special-purpose vehicle that can transport blades at a tilted angle.

Figure 4 — Available Services and Benefits of Hitachi's Total Service for Wind Turbine Blades

The service provides customers with a one-stop shop, with capabilities that extend from blade inspection to maintenance planning and repair.



OT: operational technology AI: artificial intelligence
* Comparison with previous Hitachi Power Solutions model

2. 4 Demolition and Replacement

While onshore wind power generation capacity is expected to grow in the future, wind farms built in the early 2000s are now approaching the end of their lives. If this capacity is not to be lost, they will need to be replaced. Hitachi Power Solutions has entered into an agreement with Besterra Co., Ltd. to license their patented technique for taking down wind turbines for demolition(6). After the blades have been removed, the wind turbine tower is cut at its base and the tower brought down onto a previously prepared pile of earth for disassembly. The ability to accurately control the direction in which the tower falls means the procedure is very safe and it avoids the cost of having to transport and assemble a large crane (see **Figure 5**). The procedure is particularly suited to sites with only a small number of turbines and it cuts the cost by about half. Hitachi Power Solutions has built more than 480 wind turbines to date. As some of these are now approaching the end of their lives, having an efficient demolition technique encourages their replacement.

Figure 5 — Technique for Taking Down Wind Turbines for Demolition

After the blades have been removed, the wind turbine tower is cut at its base and the tower is brought down onto a previously prepared pile of earth for disassembly. The procedure is very safe and it avoids the cost of having to transport and assemble a large crane.

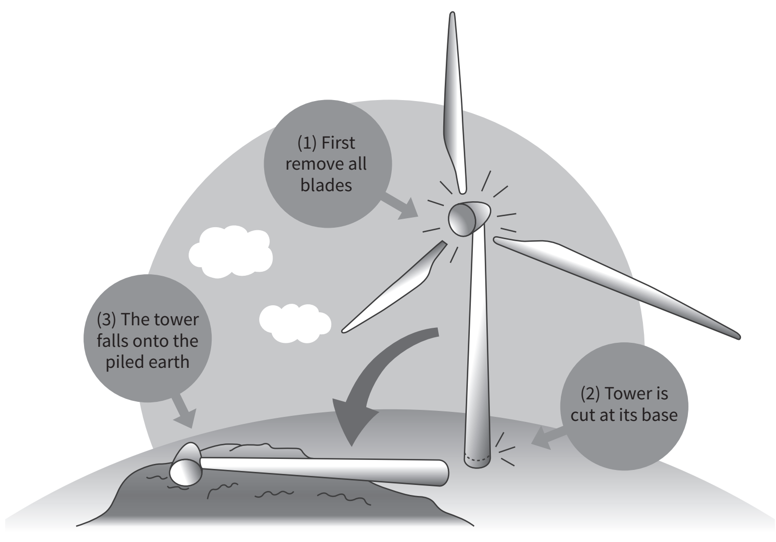
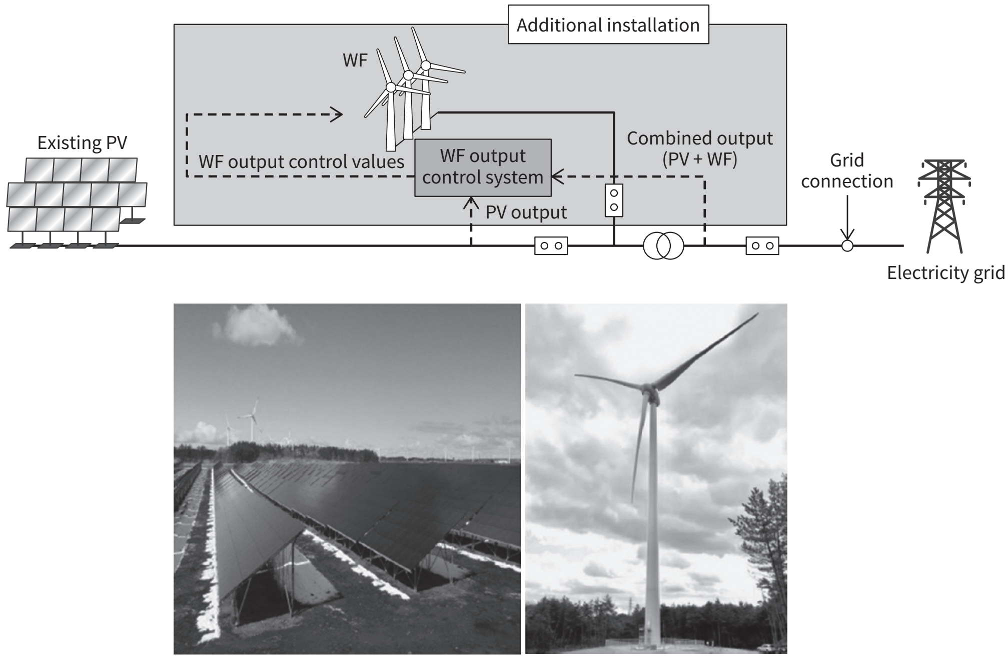


Figure 6 — Block Diagram and Photographs of Wind Power Generation System that Interoperates with Photovoltaic Power Generation

The block diagram shows the system configuration (top) and the photographs show an operating photovoltaic power plant (bottom left) and a subsequently installed ENERCON wind turbine (bottom right).



PV: photovoltaic WF: wind farm

3. Example Installations

Hitachi Power Solutions draws on technology and expertise built up through its work on installing wind power generation systems to supply a range of solutions that meet the needs of customers. The following are some notable examples.

(1) Wind power generation system that interoperates with photovoltaic power generation

One of the issues with photovoltaic power generation is that its grid interconnection capacity goes unused for much of the time, at night or when the weather or other conditions are unfavorable. In response, Hitachi has developed a wind power generation system that interoperates with photovoltaic power generation. It works by installing additional wind power generation alongside an existing photovoltaic power plant and controlling its output so as not to exceed the grid interconnection capacity. The system has been supplied to the Rokkasho-Mura Integrated Wind and Solar Farm, a joint venture between Denkosha Corporation, Saisan Co., Ltd., and Shinwa Energy Inc., where it commenced operation in March 2023[(7)] (see **Figure 6**). The estimated benefit is a more than 20% improvement in interconnection capacity utilization compared to the photovoltaic power plant on its own. In the future, Hitachi intends to take advantage of its engineering skills and expertise to market optimal and customized versions of this system to photovoltaic power system operators with excess grid interconnection capacity. This includes calculating the maximum output of the existing photovoltaic generation based on factors such as solar irradiance and determining how much wind capacity can be added based on the wind conditions and commercial considerations.

(2) Wind turbine replacement

As the useful life of a wind turbine is typically about 20 years, turbines installed in the early 2000s are now coming due for replacement. Hitachi Power Solutions undertook the replacement of 24 E-40 turbines that commenced operation in 2001 at the Noshiro Wind Farm of Tohoku Sustainable & Renewable Energy Co. Inc. (TOUSEC), installing seven E-82 turbines in 2021 at what is now the New Noshiro Wind Farm[(8)]. While the wind farm now has fewer turbines, the longer blades mean that generation output is expected to be about 20% higher. As most of the wind turbines coming due for replacement are small to medium in size, the increased generation efficiency that comes with longer blades and larger size is an attraction. Through the replacement of aging turbines, Hitachi intends to maintain and expand total wind power generation capacity.

4. Conclusions

Solid progress on making the transition to a decarbonized society is needed to address climate change, an area that has seen rapid growth in action over recent years. Use of renewable energy, as epitomized by wind power generation, is one effective means of helping to overcome this challenge. As described in this article, a characteristic of Hitachi Power Solutions is that it works in partnership with customers, providing a one-stop service for every step of the process from the early stages of a wind power generation project to operation and ultimately demolition. In the future, the company intends to contribute to the creation of a decarbonized society by holding true to this ethos and drawing on skills and expertise built up over many years to deliver wind power generation solutions that help to resolve challenges for customers and wider society.

Acknowledgements

Sensyn Robotics, Inc. provided considerable assistance with the inspection technique for turbine blades described in this article that uses drones and AI. Besterra Co., Ltd. likewise provided assistance with the technique for wind turbine demolition. The authors would like to take this opportunity to express their deep gratitude.

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Design and Construction of Changhua Offshore Wind Farm in Taiwan

The installation of offshore wind power generation is expanding internationally as it comes to be recognized as a major form of renewable power generation for achieving carbon neutrality. Having been commissioned by the Taiwan Power Company to supply a wind power generation system for the Changhua Offshore Wind Farm, Hitachi and Jan De Nul nv of Luxembourg completed installation of wind turbines in June 2021. Operation commenced in December that same year. The quality assurance process used in the wind power industry includes a third-party agency that verifies and certifies wind turbine designs, with certification being done on a per-project basis in the case of offshore wind power generation projects. This article explains how Hitachi went about acquiring certification for the Changhua Offshore Wind Farm project, also describing the challenges of its first offshore wind installation project and how these were addressed.

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Ikuo Tobinaga, P.E.Jp.
Soichiro Kiyoki

1. Introduction

By the conclusion of the 26th United Nations Climate Change Conference of the Parties (COP26) in November 2021, commitments to achieve carbon neutrality by a given date had been made by a total of 154 countries and one region. Having competed to set ambitious goals for action on climate change, countries are now entering the implementation stage where they need to decide how they are going to fulfill these commitments[(1)]. Making the transition to sustainable energy systems is essential to decarbonization. Wind represents one way of generating electric power that does not emit carbon dioxide (CO_2), with offshore wind turbines in particular benefiting from steadier wind conditions than are found on land and the ability to install large turbines without the sort of constraints imposed by difficult terrain and roads. For this reason, offshore wind power generation has come to be recognized for its potential as a major form of renewable energy, with more and more such capacity being installed around the world, especially in Europe. Recent years have also seen rapid growth in Japan and Taiwan as well as other Asian markets.

Hitachi, Ltd. and Jan De Nul nv (JDN)[(2)] of Luxembourg received an order from the Taiwan Power Company[(3)] to supply 21 5.2 MW wind power generation systems (with a total output of 109.2 MW) for the Changhua Offshore Wind Farm. The combined deal covers equipment manufacture and installation as well as a five-year operation and maintenance (O&M) contract. Turbine installation was completed in June 2021 and the 21 units commenced operation from December of that year (see **Figure 1**).

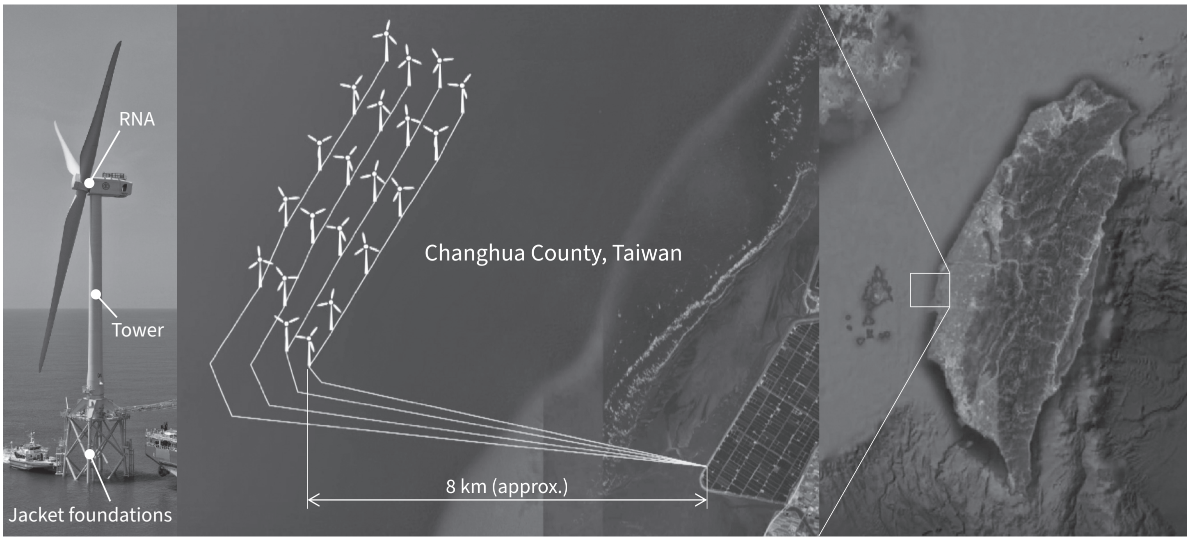
This article describes some of Hitachi's work on design and construction for the Changhua Offshore Wind Farm[(4)].

2. Design of Support Structures for Offshore Wind Power Generation Systems

The quality assurance process used in the wind power industry includes a third-party agency that verifies and certifies wind turbine designs. Hitachi's HTW5.2-127 wind power generation system is designed for offshore installation. Its design was certified by the DNV AS[(5)] certification agency of Germany and type certification was obtained from Nippon Kaiji Kyokai (ClassNK)[(6)]. As the environmental conditions for offshore wind projects vary widely

Figure 1 — Changhua Offshore Wind Farm in Taiwan

Hitachi and JDN built this offshore wind farm (21 5.2 MW wind power generation systems with a combined output of 109.2 MW) located about 8 km off the coast of Changhua County, Taiwan.



RNA: rotor nacelle assembly

from project to project, including the type and depth of the seabed, the support structures (tower and foundations) are verified separately for each project in a process called "project certification." Similarly, while the rotor nacelle assembly (RNA) receives type certification in advance, its strength is also reviewed for each project based on the applicable design loads.

The design team for the Changhua Offshore Wind Farm was comprised of Hitachi, JDN, and COWI A/S(7), a large Danish engineering company. It took approximately 18 months to complete the support structure design based on use of jacket foundations and obtain project certification.

2. 1 Determination of Design Criteria

The design of the support structures for the Changhua Offshore Wind Farm turbines needed to address three different design criteria (Design basis A: General project requirements, Design basis B: Wind turbine design requirements, and Design basis C: Foundation design requirements). These included the following items.

(1) Site conditions (including wind, metocean, seabed, and seismic conditions)

(2) Applicable standards or codes and other additional requirements (such as customer-specified specifications)

(3) Design criteria [including design wind speeds, design loads (extreme and fatigue loads), and safety margins]

(4) Manufacturing, transportation, installation, and commissioning requirements (including specifications, quality management system, and transportation methods)

(5) Operation and maintenance requirements (target structure life, inspection scope and frequency)

(6) Generation system type (wind turbine specifications and requirements)

To put together this set of design criteria, the design team from Hitachi, JDN, and COWI consulted with one another to identify the relevant standards, select a certification agency, determine the design conditions (including the number of different foundation types and iterative computation cycles), decide on the software to use for the calculations and what data conversion methods to use, and determine the site conditions.

Hitachi uses both actual measurements and simulation to determine the design wind speed. This was done using data collected from a meteorological mast installed by the Taiwan Power Company in the ocean near where the turbines were to be installed. As the intermittent nature of typhoons makes it difficult to estimate extreme wind speeds from a short term of observations, simulation was also used to determine the design wind speeds.

2. 2 Determination of Design Loads

A table of design load cases was determined on the basis of site-specific conditions, including wind, waves, currents, and the seabed. Because this covered a very large number of cases, the table was then narrowed down to a smaller set of conditions in consultation with the certification agency (for this project, approximately 7,000 cases per wind turbine). The wind turbines for the project were grouped into clusters based on sea depth, and the design loads were estimated using the superelement method for three types of jacket foundations (deep, intermediate, and shallow) (see **Figure 2**)(8).

COWI first used the Sesam* engineering software for offshore structures to build a model of the foundations and analyze it under wave load conditions. Next, the foundations model was consolidated into a modal model called a "superelement" that is made up of modal mass and modal stiffness matrices. This was supplied to Hitachi along with the wave loads. Hitachi used the Bladed* wind turbine design software to perform a coupled analysis of the foundations and wind turbine that combined the superelement model of the foundations from COWI with a turbine model. This was used to calculate the loads on the turbine. Finally, the time-series loads obtained by the Bladed analysis for the interface node between the tower and foundations were supplied back to COWI where they were used together with the wave loads to re-run its analysis and calculate the loads on the foundations. On this project, this sequence of steps went through three iterations to optimize the support structures and determine the design loads (extreme and fatigue loads).

2. 3 Primary Structure Design and Design for Temporary Construction

Primary structure refers to the main structural elements, including the jacket foundation beams, tower shell, and flange. It must have the required structural strength. This design is normally completed based on a structural strength analysis using the design loads discussed above.

In the case of offshore wind projects, however, preassembly is performed in port due to the need to keep the installation time and number of crane lifts to a minimum, as explained below. Because the assembled tower on its own has a higher natural frequency than the completed wind turbine (when the weights of the nacelle and rotor are attached to the top of the tower), the risk of vortex-induced vibration (VIV) needed to be taken into account. VIV refers to vibrations generated by the vortices that form when wind flows around the cylindrical cross-section of the tower. While procedures for estimating VIV loads are given in standards and guidelines, the pre-assembled towers are stored alongside one another where their mutual influence is difficult to analyze and assess. It is also important to estimate structural damping as this is a crucial analysis parameter.

To address VIV, Hitachi fitted helical strakes on the towers and used European standards to conduct a structural analysis of the towers during the preassembly and transportation phase. Structural damping was verified using actual measurements in port and on the installation vessel.

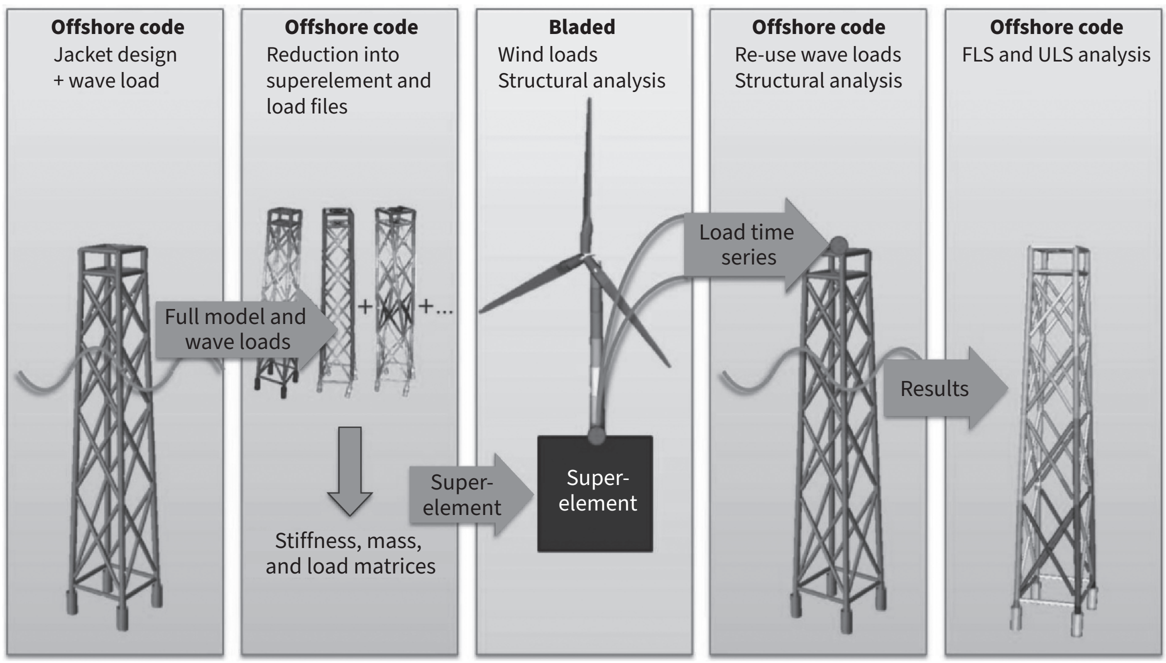
2. 4 Secondary Structure Design

Secondary structures are the ladders, decks, and guard rails fitted on the tower and jacket foundations. The design of

* Sesam and Bladed are trademarks of DNV AS.

Figure 2 — Superelement Method

A coupled analysis of the foundations and turbine was implemented by combining a superelement model of the foundations supplied by COWI with a turbine model. This was used to calculate the loads on the turbine. The results were then supplied back to COWI where they were used to recalculate the loads on the foundations.



FLS: fatigue limit state ULS: ultimate limit state these structures needs to address both functional and safety considerations. The preparation of a maintenance plan is likewise important.

In terms of function, because access to the offshore wind power generation systems happens many times from the construction phase to the maintenance phase, it is necessary to take account of the environmental conditions at the site and ensure that design choices such as deck location and height, number of access points, and deck shape allow for access to and from the structure by people and equipment under a wide range of sea conditions.

For safety, the design included verification of compliance with the relevant safety standards while also making allowance for the replacement of consumables and parts that could potentially fail.

3. Installation of Offshore Wind Power Generation Systems

3. 1 Challenges of Offshore Installation Work

This section describes the challenges associated with installing offshore wind power generation systems.

(1) Construction cost

Offshore wind turbines are generally installed using a jack-up vessel (JUV). Because a JUV costs a lot more than the equivalent construction machinery used on land, it is necessary to keep the installation time and number of crane lifts to a minimum (see **Figure 3**). Accordingly, measures were taken to make the task easier, including the pre-assembly of the towers, selection of an asynchronous turning motor, and simplification of the parts around the blade attachment area.

(2) Environmental conditions

The ability to undertake work at sea is constrained not only by wind speed, but also by the sea and weather conditions. Accordingly, detailed planning went into the work to allow for interruptions due to accidents or the weather, including a work plan, backup plans, and the on-the-fly scheduling of installation staff shifts.

(3) Limit on staff numbers

While a variety of staff needed to be onboard the JUV, including the vessel's crew, project manager, marine insurance assessor, and customer personnel, the number of staff needed to install the wind generation systems was limited by the capacity of the ship's cabins. To overcome this, installation apparatus was built to enable the work to be done quickly and with a small number of people.

(4) Certification of equipment used in transportation

Standard practice in the construction of offshore wind turbines is that permission for the use of any additional apparatus in the work is obtained by having a third-party verify that it has been designed and fabricated correctly in accordance with the relevant standards. Once a decision is made on the transportation vessel and how the transported parts are to be stowed, this third-party verification involves determining the different loading cases based on ship movement (acceleration), gravity, and wind and then performing a strength analysis for this apparatus and other equipment.

(5) Certification of equipment used in installation

Confirmation is also required that the lifting and other apparatus used in installation has been designed in compliance with the relevant standards and guidelines. Similarly, verification testing is required to confirm that this apparatus can withstand the loads to which it will be subject in practice. Factory inspections are also conducted to ensure that it has been fabricated in accordance with the design. This includes confirming that compliant products have been used for all general-purpose equipment (such as slings, shackles, and lifting bags).

3. 2 Successful Completion of Offshore Installation

The Hitachi and JDN construction team commenced work in June 2020 and completed the installation of all

Figure 3 — Offshore Turbine Installation in Progress

Installation of the wind turbines at sea was done using a jack-up vessel (JUV). The project installed 21 wind turbines, with individual installations able to be completed in as little as 22 hours or less.

21 offshore wind power generation systems in June 2021, including a period when work was halted for a time due to COVID-19. Thanks to the optimization of the design and of working practices, installation of an offshore wind turbine was able to be completed in as little as 22 hours or less.

4. Conclusions

This article has described the design and installation work successfully undertaken by Hitachi for the Changhua Offshore Wind Farm. Hitachi also intends to utilize the knowledge and experience gained from this project to contribute to the development of the offshore wind power business.

Acknowledgements

Considerable assistance was received from the other stakeholders in the design and installation of the Changhua Offshore Wind Farm in Taiwan described in this article, including Hitachi's consortium partner Jan De Nul nv, the foundation design company COWI A/S, the customer Taiwan Power Company, and the DNV AS certification agency. The authors would like to take this opportunity to express their deep gratitude.

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Future Digital Solutions for Power Distribution that Enhance Economic and Social Value

Along with the reliable and economic supply of electric power, another important consideration for power transmission and distribution business operators is that they contribute to sustainable regional development. Hitachi has been consolidating the work it has done investigating potential future digital solutions for power distribution that will enhance both economic value for power transmission and distribution business operators and social value for communities. The goal is to build solutions that improve both economic and social value by combining digital twins of power distribution with cross-industry applications. This includes applications that deliver social value by optimizing practices at a regional level through integration of the information and systems belonging to real estate developers, transportation operators, public agencies, and other local stakeholders, with the digital twins serving as tools for the centralized management of a wide range of information relating to power distribution.

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Keiro Muro
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Akira Murata

1. Introduction

In Japan, electric power is mainly generated at power plants by generation operators and delivered to the consumers who need it by power transmission and distribution business operators (general power transmission and distribution business operators, power transmission business operators, and specified power transmission and distribution business operators) using transmission lines, substations, and other distribution infrastructure. While the reliable delivery of electric power is the top priority for these companies, they also need to consider commercial viability if they are to remain in operation.

Furthermore, most power transmission and distribution business operators have close ties to their region and are committed to resolving societal challenges and supporting the ongoing development of their local communities. Along with economic value for themselves, this means that enhancing social value for the entire community and region is another important consideration.

Given this environment, Hitachi has been considering the way forward for digital solutions for power distribution that can enhance social value in their regions as well as economic value for power transmission and distribution business operators and the companies from the local community that are likely to play an essential role in the future.

2. Grand Design for Digital Maintenance Platform Service for Power Distribution and the Value it Delivers

As noted above, the reliable delivery of electric power is the top priority for power transmission and distribution business operators. As standalone businesses, it is also important for these companies to reduce their operating and maintenance costs without compromising security of supply. In recent years, they have also had to deal with the emerging challenges of workforce shortages and aging equipment. To address these challenges, these companies have sought to enhance their own economic value by pursuing business process re-engineering (BPR), upgrading their information systems in tandem with a redesign of their workflows and organizational restructuring. They are also adopting more advanced systems, including efficiency gains from artificial intelligence (AI) and the use of drones to automate visual inspection work. To do so, they need to be integrating the enterprise asset management (EAM) systems they use for maintaining transmission and distribution infrastructure with newly installed AI platforms and other systems for Internet-of-Things (IoT) sensors, robots, and three-dimensional city models. Given that advanced systems like these are progressing at a rapid pace, the development of functions for EAM integration also needs to be made easier.

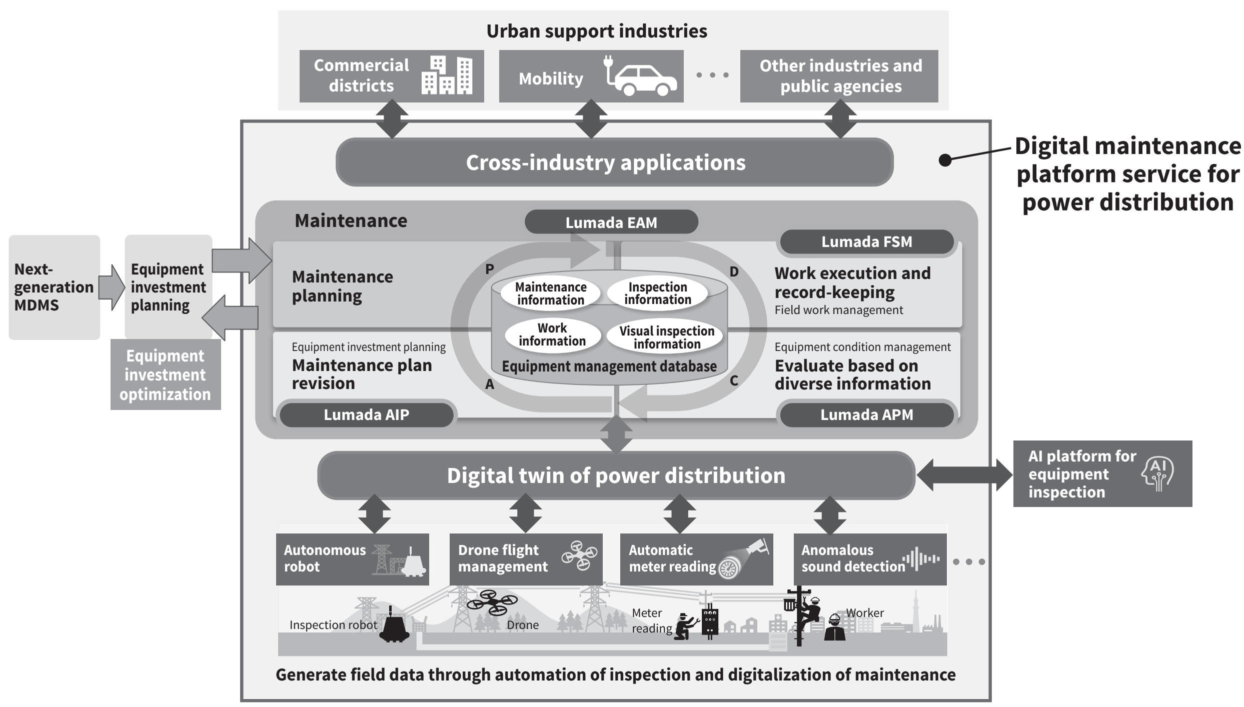
In response, Hitachi is building digital twins of power distribution for the centralized management of a wide variety of information on electricity distribution. These replicate real-world distribution systems in a digital space, including historic data. The shared use of these digital twins by other systems smooths and simplifies the integration of EAM with other advanced systems.

Meanwhile, along with raising their own economic value, enhancing social value for the entire community and region is another important consideration for power transmission and distribution business operators. As reported elsewhere(1), an essential requirement for creating sustainable societies is to achieve the best outcome for everyone by also coordinating operation with the information and systems belonging to real estate developers, transportation operators, public agencies, and other stakeholders in the local community.

To do so, Hitachi has developed a suite of cross-industry applications for resolving the sort of societal challenges that are difficult for individual organizations to address on their own, and which work by linking the digital twins

Figure 1 — Block Diagram of Digital Maintenance Platform Service for Power Distribution

The service smooths and simplifies the integration of EAM with a wide range of systems, such as those for AI, IoT sensors, and robots. It does this by creating digital twins of power distribution that provide centralized management of a wide range of information relating to power distribution, thereby replicating the actual environment for power distribution infrastructure in a digital space.



MDMS: meter data management system AIP: asset investment planning EAM: enterprise asset management FSM: field service management
APM: asset performance management AI: artificial intelligence IoT: Internet of Things PDCA: plan, do, check, act

of power transmission and distribution business operators with the operational systems of other stakeholders such as real estate developers and transportation operators. These link the information handled by digital twins with the operational systems belonging to the many different organizations involved in running a city, such as those for commercial districts or mobility. The resulting social value includes the optimization and reallocation of resources across entire communities.

Finally, Hitachi is contributing to enhancing economic value for power transmission and distribution business operators and social value for local communities by providing a digital maintenance platform service for power distribution in the form of a total solution that combines EAM with the digital twin of power distribution, advanced systems, and cross-industry applications (see **Figure 1**).

The following sections describe the digital twin of power distribution and the cross-industry applications that are key components of the digital maintenance platform service for power distribution.

2. 1 Digital Twin of Power Distribution

In the digital maintenance platform service for power distribution, the digital twin of power distribution handles three-dimensional data on distribution infrastructure and on buildings and other urban facilities (see **Figure 2**). The procedure for doing so is as follows.

(1) Step 1 is to replicate simplified building information modeling (BIM) data in the digital twin of power distribution from equipment management data in EAM. In this step, the level of detail (LoD) of the models managed by the digital twin of power distribution is low and they are "as-designed" models that show the equipment as it was designed in the original plans.

(2) Step 2 improves the LoD of the overall model by progressively increasing the precision of position data for each object in the digital twin using point cloud data collected onsite. As this data records the actual form of the equipment, it means that the digital twin can now work with "as-built" model data.

(3) Step 3 is to keep the model data in the digital twin up to date by re-acquiring the point cloud data each time the site is inspected. That is, the digital twin is able to maintain "as-is" model data depicting the current state of the equipment.

While step 3 provides as-is model data with the highest LoD, more cost and effort are involved in its acquisition and administration. For this reason, a more pragmatic approach is to only progress along as many steps as is warranted given the importance of the equipment concerned.

Interlinking the digital twin of power distribution with EAM gives access to EAM functions such as risk analysis and the tracking of equipment maintenance costs. This integration means that the digital maintenance platform service for power distribution can manage information as a five-dimensional model, with the three-dimensional spatial information being augmented by a time dimension (the condition of the equipment when first built, as it is now, and how it is likely to be in the future) and a cost dimension (capital and subsequent maintenance costs). Hitachi has built up expertise in the fields of power plants and transmission and distribution infrastructure over many years, including in three-dimensional spatial design and four-dimensional simulations of engineering work. By using this expertise as a basis for building five-dimensional digital twins of power distribution, Hitachi can deliver economic value to power transmission and distribution business operators in ways that include cost savings from the resolution of operational issues and the development of optimal investment plans.

Figure 2 — Example Digital Twin of Power Distribution

The data on power distribution infrastructure handled by EAM is replicated in digital space as a simple building information modeling (BIM) model. Accurate positional information is then obtained by superimposing point cloud data collected onsite and this is used as feedback to digital space.

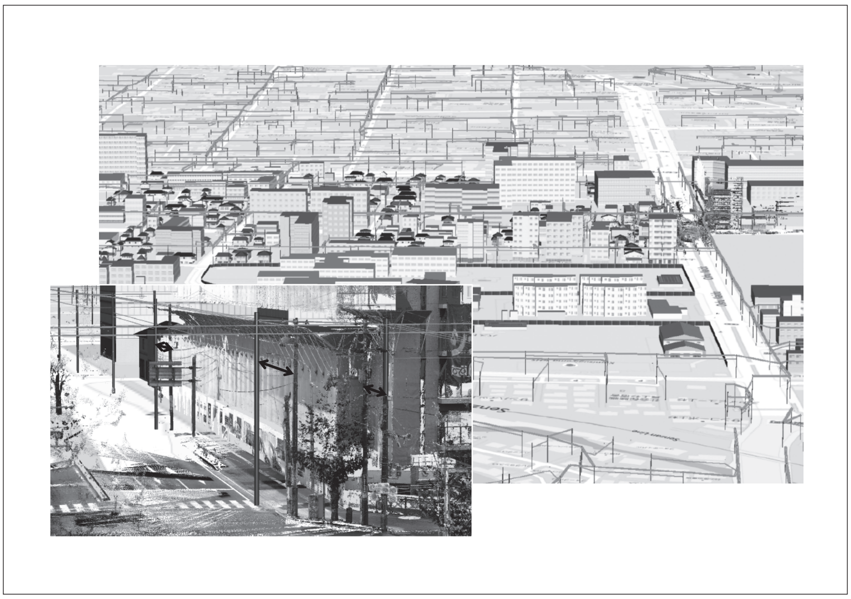
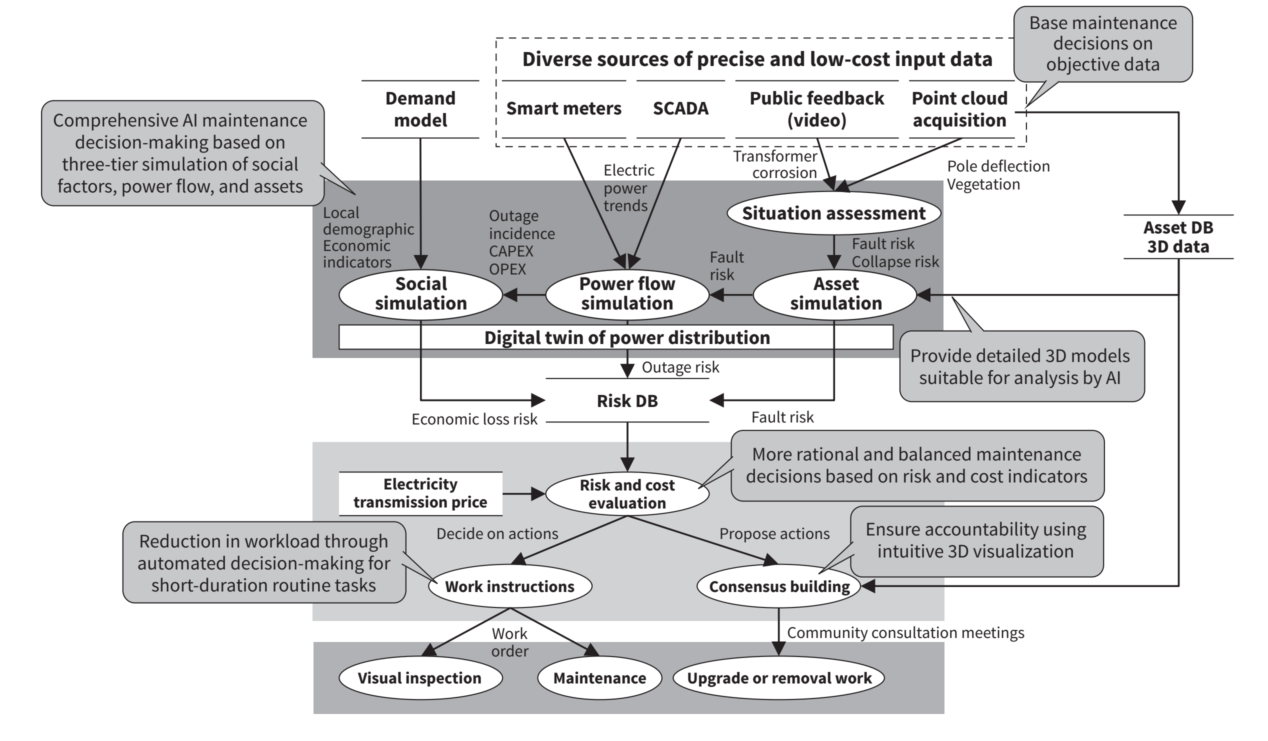


Figure 3 — New Electricity Distribution Workflow Using Digital Twin of Power Distribution

Precise and low-cost forms of input data such as point clouds are used and this is then utilized to achieve waste-free electricity distribution through comprehensive and data-driven decision-making on costs and risks that is based on social, power flow, and asset considerations.



SCADA: supervisory control and data acquisition CAPEX: capital expenditure OPEX: operating expenditure DB: database 3D: three dimensional

Figure 3 shows how a digital twin can also be used to reform power distribution workflows. The digital twin can be used to conduct a variety of risk assessments based on multiple data sources (not just point clouds), such as the risk of economic losses, power outages, or asset damage. This enables work on the distribution system to proceed in a waste-free manner, with comprehensive and data-driven decision-making on the assessed risks and costs.

2. 2 Cross-industry Applications

The digital twins of power distribution described above are a core element in the digital maintenance platform service for power distribution, which is primarily intended as a solution for improving economic value for power transmission and distribution business operators. This section describes cross-industry applications that link these digital twins to the operational systems of other stakeholders such as real estate developers or transportation operators and provide a suite of functions for resolving the sort of societal challenges that these stakeholders find difficult to address on their own. Specifically, it will describe one such application for working with real estate developers.

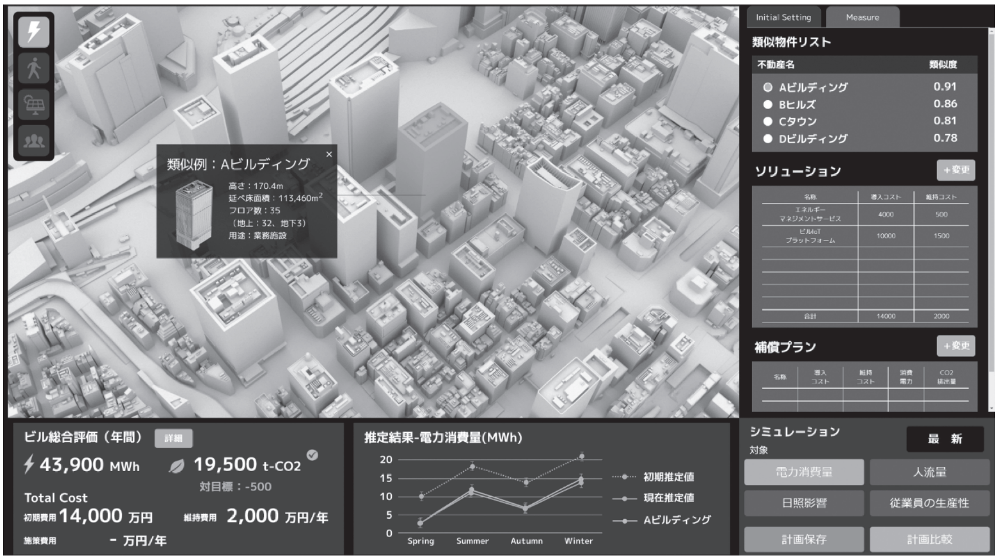
Factors that today's real estate developers need to consider include how to reduce their load on the environment and how to deal with a shift in working practices toward a mix of office work and telework. Hitachi has consulted with such developers to identify the issues that arise in development projects, whether for individual buildings or larger sites. After looking at solution ideas for using its digital twins to address these challenges, Hitachi developed its building performance indicator prediction service (see **Figure 4**). The service provides real estate developers with an efficient means of predicting performance indicators for new builds that they can use during the early stages of the core building design.

One of the issues for real estate developers is that they face high coordination costs due to the many different consultants they need to engage during the early stages of the core design for building development, making it difficult for them to assess performance indicators in terms of a complex mix of different factors. As this issue is one that also involves other stakeholders, including power transmission and distribution business operators, local government, and the community, it is not easy for developers to address on their own.

In response, the service can estimate performance indicator values for a building from the early stages of its core design when the architectural drawings and BIM are completed. It works by using performance indicators for existing buildings with similar design parameters as a benchmark, adjusting these to allow for the features of the planned site.

Figure 4 — Building Performance Indicator Prediction Service as Example of Cross-industry Application

This service provides real estate developers with an efficient means of predicting performance indicators for new builds that they can use during the early stages of the core building design.



Note: The urban model shown above was created from the 3D models of the 23 special wards of Tokyo made available by the Ministry of Land, Infrastructure, Transport and Tourism (Project PLATEAU) (https://www.geospatial.jp/ckan/dataset/plateau-tokyo23ku)

These design parameters are variables determined during the core planning and design phase, including building height, total floor area, construction area, number of floors, number of tenants, number of air conditioning systems, total window area, number of floors of each type (such as retail, residential, office, or logistics), and the type of building energy management system (BEMS) to be used. The design parameters give an indication of the neighborhood traffic volume, power consumption, and how the building will look once it enters use, allowing the development plans to be reviewed on the basis of a complex mix of factors. It is anticipated that this service will reduce the cost to real estate developers of coordination with other stakeholders and of having to make major revisions after the plans are completed. They also allow for a quantitative assessment of the development plans based on a complex mix of factors. Identifying appropriate benchmark buildings and passing on this information to the architects also allows them to settle on a direction for their development plans quickly and efficiently. As the costs associated with electricity supply infrastructure in the vicinity of the building also form part of these coordination costs, the service should also help power transmission and distribution business operators cut the expense of costing this work.

By making a number of cross-industry applications like this available, Hitachi is supporting society-wide optimization by encouraging collaboration between power transmission and distribution business operators and local community stakeholders.

3. Conclusions

This article has reviewed the outlook for digital solutions for power distribution that are likely to be an essential requirement for the power distribution industry in Japan as it experiences change in both its business environment and societal role.

By using this newly designed digital maintenance platform service for power distribution as a basis for co-creation, not only with power transmission and distribution business operators, but also local community stakeholders such as real estate developers, transportation operators, and public agencies, Hitachi will continue to create digital solutions that enhance economic value for individual stakeholders while at the same time resolving societal challenges.

Acknowledgements

Considerable assistance was received from Satoshi Imaruoka of Nihon Computer Consultant Co., Ltd. and everyone else involved in the development of the digital twin of power distribution described in this article. The authors would like to take this opportunity to express their deep gratitude.

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Distributed Energy Resources Cooperation Service

Japan has set a target of 36% to 38% renewable energy capacity for FY2030 and is working on the measures needed for renewables to become a major source of electric power. While renewable generation is subject to considerable natural variability, it is anticipated that work will be needed to address the same cost-competitiveness, generation reliability, grid constraints, and capacity balancing issues that are faced by conventional large, centralized power plants. There will also be a need for reliable and cost-effective operation of generation using distributed energy resources that will include battery energy storage as well as renewables. In response, Hitachi, Ltd. is developing a distributed energy resources cooperation service that will be equipped with the core functions needed for the operation of this electricity infrastructure, including centralized control, generation plan formulation, and electricity market trading. This article gives an overview of the solution and describes its features.

Seiji Inagaki
Junichi Miyakawa
Tomohiro Sasa

1. Introduction

As climate change and global warming become increasingly severe, there is a need to shift to a decarbonized society. In its energy policy, Japan has set a target of renewable energy making up 36% to 38% of the energy mix in FY2030. If this is to be achieved, renewable energy will need to become a major source of electric power and the design of the electricity system will need to address a number of issues if the installation of large amounts of renewable capacity is to be done sustainably. Specifically, it will be necessary to: (1) improve cost-competitiveness, (2) establish a commercial environment that supports reliable long-term generation, (3) overcome grid constraints, and (4) ensure adequate balancing capacity.

Against this background, the shift from a feed-in tariff (FIT) to a feed-in premium (FIP) regime for renewable generation and the use of thermal power generation and pumped storage hydro to provide the balancing capacity that is essential for coping with the natural variability of renewable energy are also being accompanied by progress on the adoption of next-generation technologies for carbon-free balancing capacity. Among the technologies seen as having an important role to play in providing this flexible and efficient balancing capacity are virtual power plants (VPPs) that balance supply and demand by using the Internet of Things (IoT) for integrated control of resources such as power generation equipment and battery energy storage that are spread around the community, grid batteries that help maintain the stability of the electricity grid, and power-to-gas facilities that use electricity to produce and store hydrogen. As these demand-side energy resources differ from large power plants in that they are spread across different consumers, work is having to be done to integrate them into the power system. Japan has also seen the creation of what are defined in the Electricity Business Act as “specified wholesale suppliers,” meaning electricity supply businesses that aggregate these distributed energy resources, acting as intermediaries between consumers and generation operators to control the balance of electricity supply and demand and maximize the use of demand-side energy resources.

This article describes the work Hitachi is doing on its distributed energy resources cooperation service for overcoming the operational challenges posed by these assets.

2. Distributed Energy Resources Cooperation Service

The distributed energy resources cooperation service is a platform that delivers services primarily for small and medium-sized operators of distributed energy, enabling them to operate and monetize these resources. It includes functions for trading on the Japan Electric Power Exchange (JEPX) and for submitting generation plans to the Organization for Cross-regional Coordination of Transmission Operators, Japan (OCCTO) by collating information on distributed sources of electricity supply and consolidating them into VPPs. **Figure 1** shows some of the use cases envisaged at the time of writing for the operation of distributed energy resources on the electricity grid.

2. 1 Development of Distributed Energy Resources Cooperation Service

To implement these use cases, Hitachi has set about transforming this support for distributed energy into a service that utilizes the CURSUS package it has deployed in its own electric power business and that includes functions needed to coordinate the operation of distributed energy resources with the market (see **Figure 2**). In FY2022, Hitachi developed a renewable energy aggregation service for FIP operators who focus on renewable energy generation (use case 6 in **Figure 1**). This handles the trading of renewable energy generated from multiple sites and the submission of generation plans.

The main system functions are as follows.

(1) Prediction of renewable generation output

Because it is impossible to control how much renewable energy can be generated from the wind or sun, a function is needed to predict output based on weather and other inputs. This function collates the output predictions from multiple distributed generators to predict total generation from a given area and it can also take input from other prediction systems that are able to output their generation estimates as comma-separated-value (CSV) files.

(2) Formulation of generation plans

This function creates generation plans automatically from predicted output and contracted demand. To maximize generation revenue and ensure fulfillment of demand and supply contracts, it can calculate the excess or shortfall in electric power by matching the planned output of each generation plant against demand. By inputting market price predictions, it can also determine the optimal bids to make on the electricity trading market.

(3) Trading on JEPX spot market

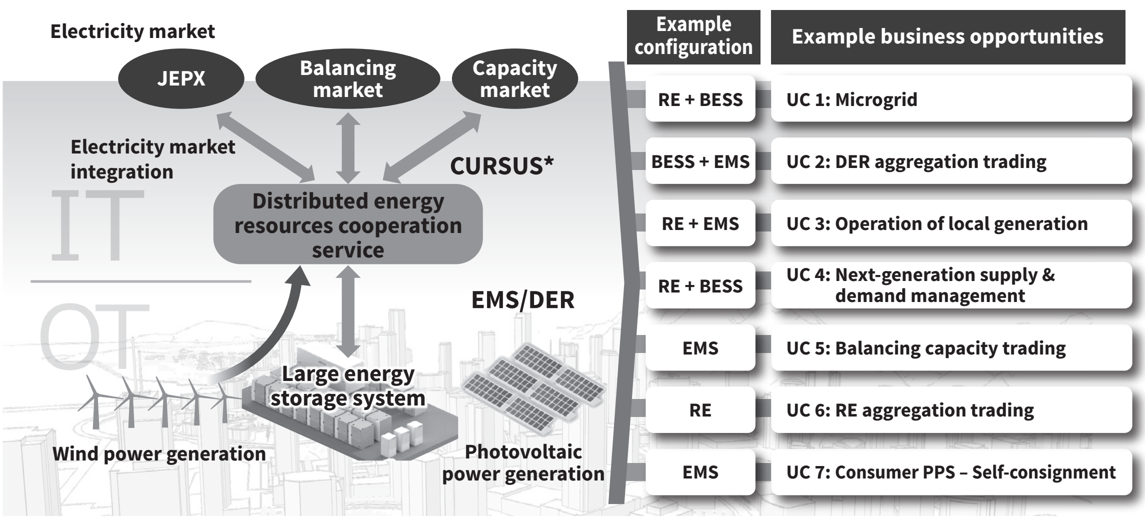
The system is able to bid on the JEPX spot market using its built-in trading interface. The bidding outcomes are also acquired from JPEX and generation plans are updated automatically by reassigning the contracted amount of electric power to the available generators.

(4) Submission of generation and sales plans

Generation operators and contract counterparties are required to submit generation and sales plans to the OCCTO in accordance with the Electricity Business Act along with contract provisions such as available transmission

Figure 1 — Overview of Distributed Energy Resources Cooperation Service

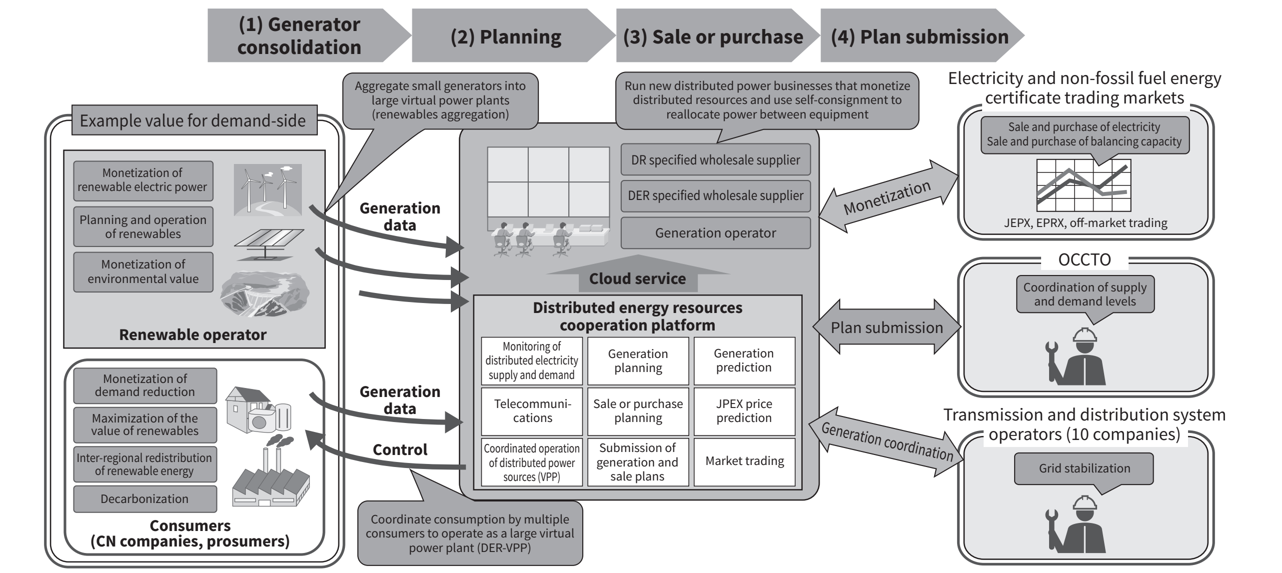
The distributed energy resources cooperation service helps make use of electricity markets and the grid in power system operation, using the Internet of Things (IoT) to consolidate and administer management systems for the distributed power system assets of electricity consumers.



JEPX: Japan Electric Power Exchange EMS: energy management system RE: renewable energy DER: distributed energy resources UC: use case
BESS: battery energy storage system OT: operational technology PPS: power producer and supplier
* Package solutions such as the CURSUS-VPP solution for virtual power plants (VPPs)

Figure 2 — Block Diagram of Distributed Energy Resources Cooperation Service

Renewable energy aggregation involves functions for collating the plans and predictions of individual generation systems together with demand plans, selling or purchasing electricity on the wholesale market to deal with any excess or shortfall, and submitting generation sales plans based on the resulting sales or purchase contracts.



CN: carbon-neutral EPRX: electric power reserve exchange DR: demand response OCCTO: Organization for Cross-regional Coordination of Transmission Operators, Japan

capacity. The generation and sales plans created by the system are passed along with the required data to the input support tool provided by OCCTO for plan creation.

The system includes a user interface for using and reviewing these functions, with information such as generation predictions and contracted demand able to be plotted on trend graphs. It has also undergone testing within Hitachi where it was used in tandem with a wind power generation prediction system for an actual wind power generation system.

2. 2 Omika Green Network

Having built up a variety of skills and expertise on how to decarbonize the different facilities at the site, Hitachi's Omika Works has devised the Omika Green Network (OGN) for working on decarbonization in partnership with stakeholders in an effort to achieve carbon neutrality across all sectors of society. This has included trialing use of the distributed energy resources cooperation service to reduce carbon emissions from onsite power generation, using optimal control to coordinate low-carbon electricity procurement with power from distributed resources. This works by simulating optimal distributed power sourcing that combines the purchase of grid power with onsite photovoltaics and battery storage. **Figure 3** shows a block diagram of the OGN as of FY2022.

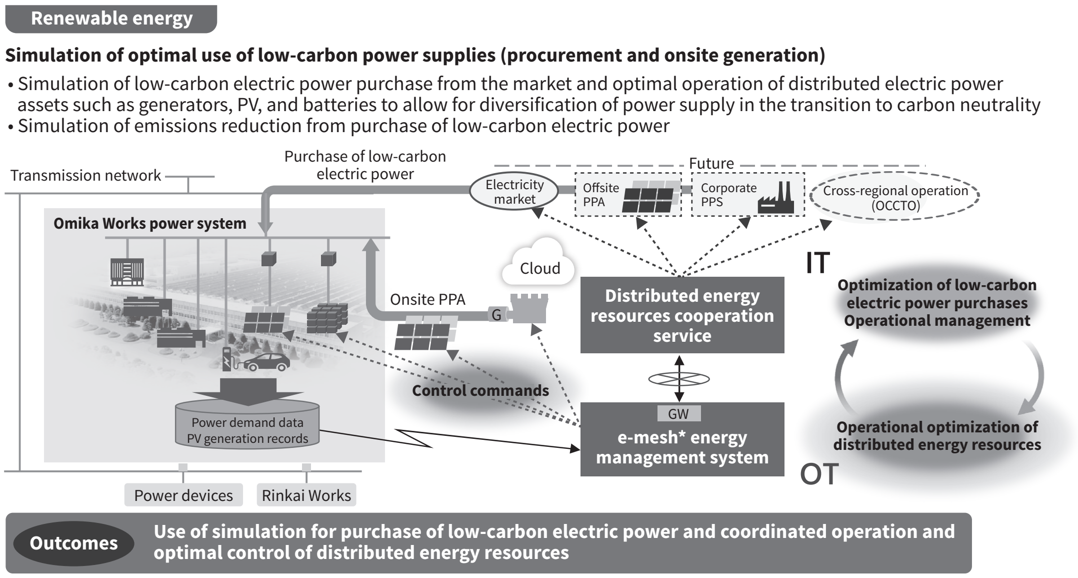
The figure shows how the distributed energy resources cooperation service is used in practice, with optimal control of these resources being implemented on e-mesh controllers from Hitachi Energy Ltd. and intelligent gateways. Generation plans and plans for the procurement of external power are formulated using the generation information passed via the gateways together with predictions for JEPX spot market prices, photovoltaic power generation, and demand. Operational instructions to the energy management system are then issued via the network.

Planning involves determining the combination of generation assets that delivers the lowest generation cost and the amount of electric power that will be generated in each 30-minute period. Operational instructions are then issued on this basis. There is also a data output function for electricity sale or purchase plans to enable procurement of the electric power needed to cover any excess or shortfall in generation capacity relative to predicted demand, with consideration of both the market price and generation plant details (such as generation cost and upper and lower limits on output).

Based on the operational instructions, the energy management system optimizes control of the distributed resources to ensure that purchased electric power is used in accordance with the plan. This involves predicting when equipment will draw high or low levels of electric power and controlling the level of purchased electric power drawn from the grid connection based on the changing load. The service is also equipped with functions for simulating changes in the operation of different generation assets, the use of excess power to charge batteries, and the dynamic response of the power system infrastructure. This includes the modeling of planned future expansions as well as existing onsite generation plant.

Figure 3 — Block Diagram of Distributed Energy Resources Cooperation Service in FY2022 Omika Green Network

The service supports efficient operation to help achieve carbon neutrality by using simulation to visualize generation and procurement as an authorized PPS consumer, including renewable energy.



PPA: power purchase agreement PV: photovoltaics G: generator GW: gateway
* A suite of grid energy solutions for distribution energy sources

It also provides planning and implementation support for decarbonization by enabling the real-time visualization of progress toward carbon-neutral electricity in terms of the trend in carbon dioxide (CO_2) emissions over any given period. This utilizes the external power purchase plans and simulation results that have been made available by this work as a basis for presenting the type of energy, quantity of electric power, CO_2 emissions, and overall trend graphs for each item of energy equipment.

3. Conclusions

This article has described a platform service that supports distributed electricity supply by helping to overcome the associated operational challenges that come with the rise of renewable energy as a major source of electric power.

Given the global trend toward treating not only existing utilities, but also “prosumers” such as off-site electricity providers and specified wholesale suppliers as electricity networks, these entities have a need for simple and reliable operation in their role as suppliers of electric power.

In the future, Hitachi intends to expand into the supply of comprehensive services that combine things like business process outsourcing (BPO) and managed services with its various divisions that deal with electric power.

By offering platforms as a service, Hitachi intends to respond with flexibility to the changing business environment that customers face as it continues working with them to achieve sustainable growth.

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Technologies for Diagnostics and Control of Lithium-ion Batteries and their Application to Energy Management

BESSs are attracting increased attention as a means of providing the balancing capacity needed to deal with the fluctuating output of renewable energy to realize power grids with high penetration of renewable energy. In order to ensure that BESSs have a long operating life and are profitable for their owners and comply with the grid constraints, there is a need for operating conditions to be optimized by diagnosing the internal state of the batteries and predicting their remaining useful life for various different charging and discharging patterns. Hitachi has been collecting battery performance and degradation information at all levels from materials to cells and systems over many years. It has also developed discharge curve analysis as a fundamental technique for battery diagnosis and control and then used it for remaining useful life diagnostics and capacity recovery. Hitachi has also applied diagnostics technology to energy management to demonstrate the validity of an imbalance risk-free system utilizing an internal balancing capacity owned by customer.

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1. Introduction

The supply and consumption of primary energy is undergoing major structural changes around the world in pursuit of carbon neutrality. Forecasts by the International Energy Agency (IEA)[1] anticipate a major reduction in the use of the fossil fuels that currently supply more than 80% of energy needs, with renewable energy such as wind turbine- and photovoltaic-power-generation becoming a major source for power grids. As grid instability is one of the challenges that come with this greater use of renewable energy, the large-scale installation of batteries is being looked at as a solution to the problem of output that fluctuates depending on weather conditions when less thermal generation capacity is available for balancing[2]. Connecting electric vehicles (EVs) to the grid is one way of using batteries for this purpose, a technology that is called “vehicle to everything” (V2X)[3]. There has also been progress on installing battery energy storage systems (BESSs) as a reliable source of electric power that is permanently connected to the grid[4]. As the batteries used in EVs and BESSs need to be compact and able to keep up with erratic changes in electricity supply and demand, lithium-ion batteries (LIBs) are widely used in these roles because of their superior energy and power densities. The market for lithium-ion BESSs targeted at consumers and generation or transmission system operators is expected to grow at an annual rate of more than 20%. Maintaining this market growth will require that BESS owners gain economic benefits from installing and operating these systems. This in turn calls for control of installation and operating costs while also boosting revenue by using BESSs to trade on electricity markets. Achieving this will require the ongoing diagnosis of battery performance and safety as these degrade with use, and also the ability to predict how the remaining useful life of batteries is influenced by how they are used. Given these capabilities, operating plans can be created that ensure both long battery life and profitability for owners.

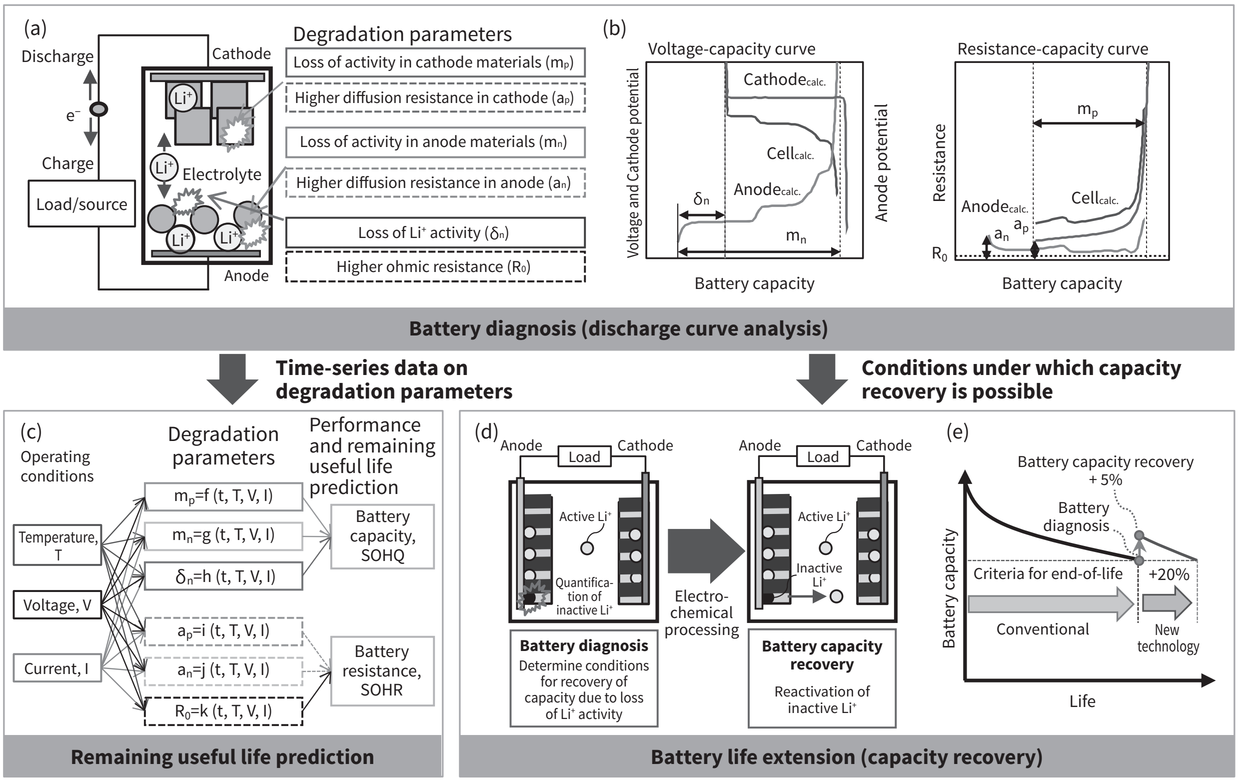
Based on its data and knowledge of battery degradation at the material level acquired from work on the development of lithium-ion cells and materials for automotive, consumer, and industrial uses, Hitachi has developed proprietary techniques for battery diagnosis and control that it is deploying in the energy storage system[4], railways[5], and construction machinery[6] industries. This article describes the core technologies for LIB diagnosis and control as well as a trial of their application to energy management in a system for eliminating imbalance risk that utilizes consumers' own balancing capacity, including EVs and BESSs.

2. Core Technologies for LIB Diagnosis and Control

Figure 1 shows some of Hitachi's core technologies for LIB diagnosis and control. The degradation of battery materials during operation depends on the operating conditions, and causes the loss of charge and discharge capacity and decreased efficiency of charging and discharging modes due to increased internal resistance. Hitachi has developed a technique called discharge curve analysis that can non-destructively identify degradation at the material level based on voltage-capacity and resistance-capacity curves for in-use LIBs[7] [see (a) and (b) in **Figure 1**]. This analysis extracts the parameters listed in **Figure 1** (a) as indicators of material-level degradation. As these degradation parameters influence the voltage-capacity and resistance-capacity curves shown in **Figure 1** (b), they can be estimated from curve analysis obtained during battery operation and used to determine the degree of degradation for each material. While similar diagnostic techniques have been widely

Figure 1 — Hitachi's Core Techniques for Diagnosis and Control of LIBs

Diagrams (a) and (b) show battery condition diagnosis. Material degradation in the battery can be estimated in the form of quantitative degradation parameters from the voltage-capacity and resistance-capacity curves obtained when charging and discharging. Diagram (c) shows remaining useful life diagnostics. By determining the dependency of these degradation parameters on operating conditions, it is possible to predict the changes in performance associated with multiple forms of material degradation. Diagrams (d) and (e) show how battery life can be extended. Degraded battery capacity can be partially recovered and the battery's life extended by manipulating the current based on the degradation parameters.



SOHQ: state of health capacity SOHR: state of health resistance LIB: lithium-ion battery investigated[8], a feature of Hitachi's technique is its broad applicability. Most of the diagnostic methods reported in the literature[9], [10] focus on the ternary lithium batteries that are widely used in automotive applications, namely those that use $Li(Ni_xMn_yCo_z)O_2$ in the cathode. This is because the strong correlation between voltage and capacity makes the diagnosis of this type of battery easy. On the other hand, in battery cell with a lithium iron phosphate ($LiFePO_4$) cathode, which contains less rare metals and exhibits the better life and cost performance, the dependence of the voltage on the capacity is relatively low. This correlation makes the diagnosis of these batteries difficult. Instead, Hitachi has been able to identify degradation parameters for these batteries by also considering the resistance-capacity curve, focusing on resistance as a more sensitive indicator of capacity[11], [12]. This method has the potential to provide precise diagnostics for the diverse range of LIBs in use by customers and on the grid.

The method can be used not only for diagnostics, but also for the prediction of remaining useful life [see **Figure 1** (c)]. The degree of battery degradation during BESS operation depends on the operating conditions (time-series data such as temperature, voltage, and current). Hitachi's diagnostic technique makes it possible to formulate the correlation between the operating conditions and the degradation parameters, which achieve the prediction of battery degradation even when various degradation reactions take place. These features allow this technique to be applied not only to the aging-aware design of BESSs, but also to efficient planning and operation considering the remaining useful life.

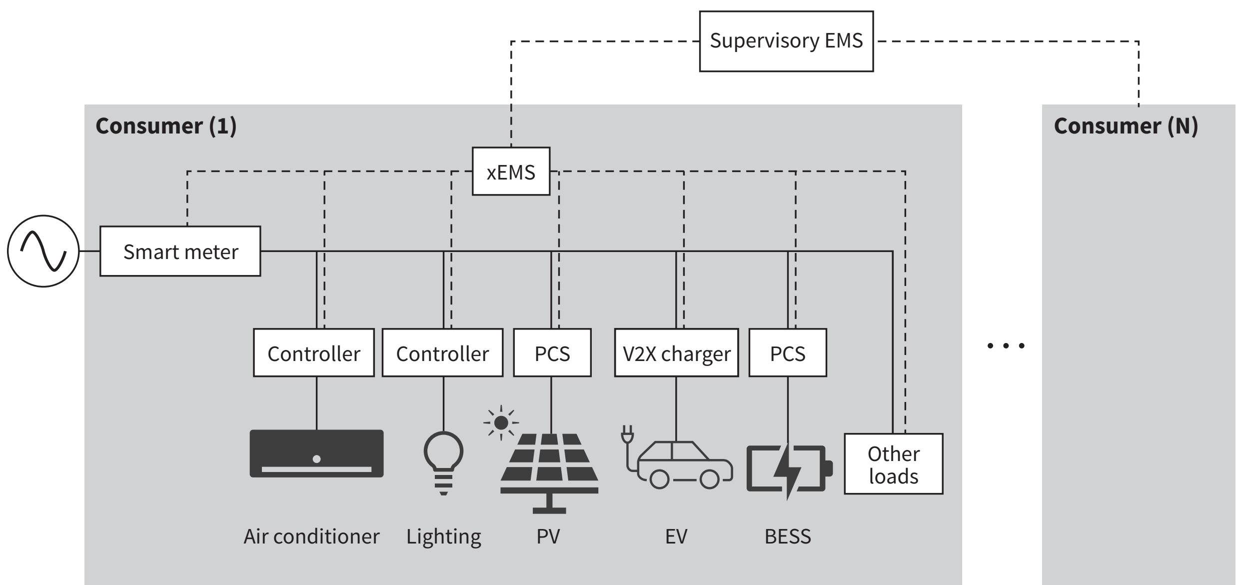
Other recent work has focused on partial recovery of degraded battery capacity based on the degree of material-level degradation, thereby extending battery life [see **Figure 1** (d) and (e)][13]. Loss of lithium ion (Li^+) activity, one of the forms of degradation listed in **Figure 1** (a), occurs when the ions become trapped in the anode where they are no longer able to contribute to charging and discharging. While it is possible to recover battery capacity by discharging beyond the lower voltage limit that applies in normal use and then temporarily raising the anode potential to expel these inactive Li^+ ions, this raises concerns that the excessive discharge will cause other materials to degrade or that it will increase the safety risk. By using the degradation parameters obtained by the diagnostic technique described above as a basis for selecting the recovery conditions, Hitachi has demonstrated that it is possible to extend battery life while suppressing material degradation and safety risk. This has the potential for application in future systems.

3. Application to Energy Management in IBRFS that Uses Customer's Balancing Capacity

If a higher proportion of energy is to be derived from renewable sources, electricity retailers will need to acquire

Figure 2 — Role of Consumers as IBRFS Customers

The diagram shows the configuration of the imbalance risk free system (IBRFS) that allows electricity retailers and consumers to coordinate their actions for autonomously balancing supply and demand.



Source: Technical Meeting on Smart Facilities, the Institute of Electrical Engineers of Japan, "Development of Demand and Supply Imbalance Risk Free System" (Sept. 2022)

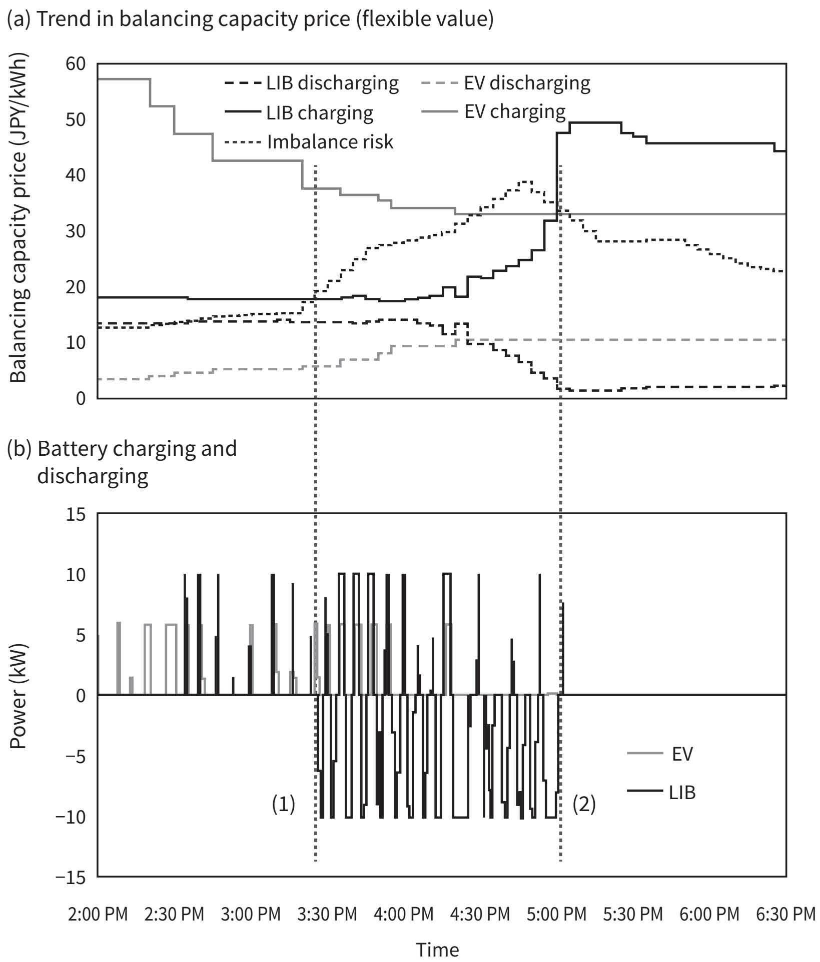
xEMS: x energy management system PCS: power conditioning system V2X: vehicle to everything PV: photovoltaics EV: electric vehicle BESS: battery energy storage system the balancing capacity needed to maintain grid stability. Hitachi has developed an imbalance-risk-free system (IBRFS) that allows electricity retailers and consumers to collectively balance their combined supply and demand, and that compensates customers for the economic cost of imbalances (imbalance risk)[14]. **Figure 2** shows a block diagram of the system. Consumer equipment includes a range of loads (lighting and air conditioning), photovoltaic (PV) power generation systems, and battery systems (bidirectional EV chargers and BESSs). The different energy management systems (xEMSs) operated by individual consumers collect data on equipment operation and on electricity consumption at the point of grid connection, passing this information to a supervisory EMS that controls operation in a way that eliminates the imbalance risk across multiple consumers. This supervisory EMS uses electricity procurement plans received from electricity retailers and data on actual demand received from the xEMSs to identify imbalances in supply and demand. It then determines how much balancing capacity can be provided by each item of equipment and issues instructions to the xEMSs accordingly. This system configuration features a high level of responsiveness and can deal with imbalances on its own, without having to go through the balancing market.

Unfortunately, because deploying balancing capacity unnecessarily can degrade equipment performance, risking a loss of remaining value, it is important to determine in advance whether the use of equipment for this purpose makes economic sense. The IBRFS uses balancing capacity price as a criterion for deciding whether equipment can be used. In the case of an electrical load, the balancing capacity price is defined as its electricity and other operating costs, whereas for a battery storage system it is the amount, per unit of energy (kWh), by which the residual value of the batteries is diminished by the degradation caused by charging and discharging. Which equipment to deploy for balancing can then be determined by comparing this balancing capacity price against the imbalance risk.

The sequence of steps for calculating the balancing capacity price for a BESS is as follows. In the case of charging, the price is calculated using formula (1) below. Discharging uses the same formula, only with different coefficient values.

Figure 3 — Results from IBRFS Trial

The upper graph (a) shows the trend in the balancing capacity price of LIB or EV charging and discharging and imbalance risk. The lower graph (b) shows how battery storage is charged or discharged in response to the balancing capacity price.



Source: Technical Meeting on Smart Facilities, the Institute of Electrical Engineers of Japan, "Development of Demand and Supply Imbalance Risk Free System" (Sept. 2022)

$$C_{battDR\_charge} = k_{charge}(SoC, T) \times C_{product}/Q_{Remaining} \quad (1)$$

C_{battDR_charge} is the base price for balancing capacity provided by a BESS and k_{charge} is a correction coefficient for increasing the frequency of balancing capacity deployment that depends on the battery's state of charge (SoC) and temperature. $C_{product}$ is the current value of the product (BESS) and is calculated using formula (2) below by amortizing its cost of purchase over its anticipated operating life. Here, $C_{product\_ini}$ is the cost of purchase, t_{Life} is the anticipated operating life (years), and $t_{product}$ is the number of years the BESS has already been in use.

$$C_{product} = C_{product\_ini}(1 - t_{product}/t_{Life}) \quad (2)$$

$Q_{Remaining}$ is the capacity (kWh) remaining over the life of the BESS. Calculated using formula (3), it represents the total amount of charging and discharging (kWh) that the battery can undergo before it reaches its end-of-life level of degradation.

$$Q_{Remaining} = Q_{Life} - Q \quad (3)$$

Q_{Life} is the amount of energy that can be charged and discharged over the battery's entire life, and Q is the amount used to date. Q_{Life} is calculated from the operating conditions using a life prediction formula. The economic benefit to the customer can be underpinned by using the degradation diagnosis and remaining useful life prediction techniques described above to calculate a highly accurate value for Q_{Life}.

The IBRFS trial described above studied the use of balancing capacity price as a criterion for responding to imbalances, using equipment installed at the research facility for this purpose, including EVs, a BESS, and other equipment likely to be found at a consumer site. **Figure 3** (a) shows time-series data for the imbalance risk and the balancing capacity prices (JPY/kWh) for a stationary LIB and EVs calculated by formula (1). The imbalance risk is the FY2020 imbalance price multiplied by a correction coefficient. This coefficient defines the margin by which the imbalance price is expected to increase relative to the historic price. Whether or not each item of equipment should be deployed for balancing is determined by comparing this imbalance risk against its respective balancing capacity price. **Figure 3** (b) shows how battery storage is charged or discharged to provide balancing capacity. Charging starts automatically to provide balancing capacity as soon as the imbalance risk increases beyond the battery's balancing capacity price, which occurs at timing (1) in the graph. As charging progresses, however, the degradation risk to the battery increases as its SoC rises, thereby increasing its balancing capacity price for charging. Accordingly, charging halts at timing (2) where this price rises above the imbalance risk.

In this way, the trial demonstrated that, by calculating accurate prices for balancing capacity and comparing these against the imbalance risk to determine which equipment to deploy, the customer's equipment can be operated in a way that maximizes revenue based on this comparison.

4. Conclusions

This article has reported on the demonstration of a system to optimize asset operation as internal balancing capacity based on the comparison between balancing capacity prices and imbalance risk as an example of the application of LIB technologies to energy management.

The technique for predicting remaining useful life serves as the basis for setting balancing capacity prices. Improving its accuracy and expanding the scope of application is important to improve the owner's revenue without compromising grid constraints and product life. To this end, Hitachi intends to contribute to enhancing customer value by further increasing the sophistication of diagnosis and control techniques for LIBs.

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Price-Performance Enhancement Using Next-generation Power Devices for Mobility Applications

Advances in the power devices, motors, batteries, and control techniques used in electric rolling stock and other mobility applications are being utilized to improve system efficiency and achieve smaller size and higher reliability. This article describes two devices from Hitachi Power Semiconductor Device, Ltd. that offer high added-value. The first is a low-loss Si-IGBT module with more than 20 times the power cycling lifetime of previous modules and the other is a SiC MOSFET module with switching losses that are less than two-thirds those of previous products provided by Hitachi Power Semiconductor Device. Hitachi has estimated the value added when these devices are used in equipment applications and compared them to devices supplied in the past. When these two newly developed devices were used to build an active-neutral-point-clamp circuit, it delivered a 140% improvement in inverter output compared to previous devices from Hitachi Power Semiconductor Device.

Katsuaki Saito, Ph.D.

1. Introduction

Hitachi Power Semiconductor Device, Ltd. has long worked to enhance the price-performance of equipment through the supply of power devices. There are three steps in this process. The first step is to define the value added in terms of the maximum output current at which the semiconductor temperature (T_j) reaches the absolute maximum rated temperature.

The second step is to consider the mission profile for the equipment in which the power device is to be used and to define the expected lifetime based on the maximum output current that will occur during operation. In the case of mobility systems, which are subject to rapid output fluctuation, the maximum output current is determined from the power cycling lifetime for the module's bonding and areas in contact with the heat sink. This maximum current is in many cases lower than the output current determined in the first step.

In the third step, the added value of the device is defined as the price-performance calculated by dividing the output power by the up-front cost subtracted by the difference in electricity running costs and battery cost [1]. As energy costs have risen in recent years due to international conflicts and renewable energy surcharges, the benefits of reducing electricity running costs have grown in importance. By incorporating detailed information about the application with the help of the customer, this analysis can calculate the price-performance, which is to say, the benefit to the customer or added value precisely.

This article describes two power devices from Hitachi Power Semiconductor Device (HPSD) that offer high added value.

2. Price-Performance Enhancement

The first of these high-added-value power devices is a silicon insulated gate bipolar transistor (Si-IGBT) module with a power cycling lifetime more than 20 times the previous modules. The other is a silicon carbide metal-oxide-semiconductor field-effect transistor (SiC MOSFET) module with switching losses that are less than two-thirds those of previous modules. With reference to the equipment in which the power devices are to be used, the added value is calculated in accordance with the first step above and compared with that of previous products.

2. 1
next High Power Density Dual

By taking maximum advantage of the high speed and low switching losses of SiC, HPSD's "next high power density dual" (nHPD²)[2] power devices reduce drive circuit inductance and cumulative current rating to 20% that of previous models. The low inductance increases the maximum power that can be handled by minimizing the voltage spikes that result from rapid switching. HPSD has been looking at how to use the package to achieve low losses, high thermal dissipation, long device lifetime, and enhanced functionality in Si as well as SiC devices.

2. 2
20-fold Improvement in Power Cycling Lifetime over Previous Devices

The Roll2Rail project has defined specifications for the power devices that railway system vendors will require in the future[3]. This requires a 20-fold improvement over previous devices in power cycling lifetime, to one million cycles at $T_{j,max}$ = 175°C and ΔT_j = 100 K[4]. Unfortunately, this is difficult to achieve with conventional bonding using solder and aluminum (Al) wire. Recognizing that a longer power cycling lifetime provides a quantitative boost to system value, HPSD has been working to improve this parameter[5]. In the latest generation of semiconductor chips, power cycling lifetime has been considerably enhanced by using sintered copper on the bottom surface of the chip and high-strength materials for the electrodes and wires on the top side (see **Figure 1**).

Figure 1 — Diagrams of Devices with Enhanced Power Cycle Performance

Image (a) was taken by a scanning electron microscope and shows the sintered copper layer under a chip, diagram (b) shows the module cross-section, and image (c) is the cross-section of a high-strength electrode and wire bonding.

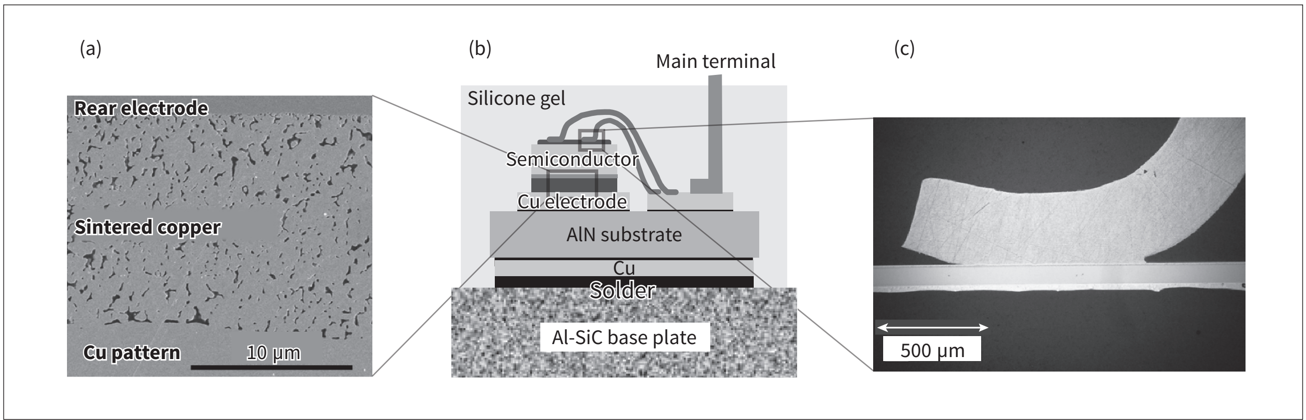


Figure 2 — Verification of Power Cycling Lifetime

Graph (a) shows the trend in ΔT_j over the course of power cycle testing, (b) shows the sequence of steps for calculating the lifetime for a given mission profile, and (c) shows the relationship between predicted lifetime and maximum current.

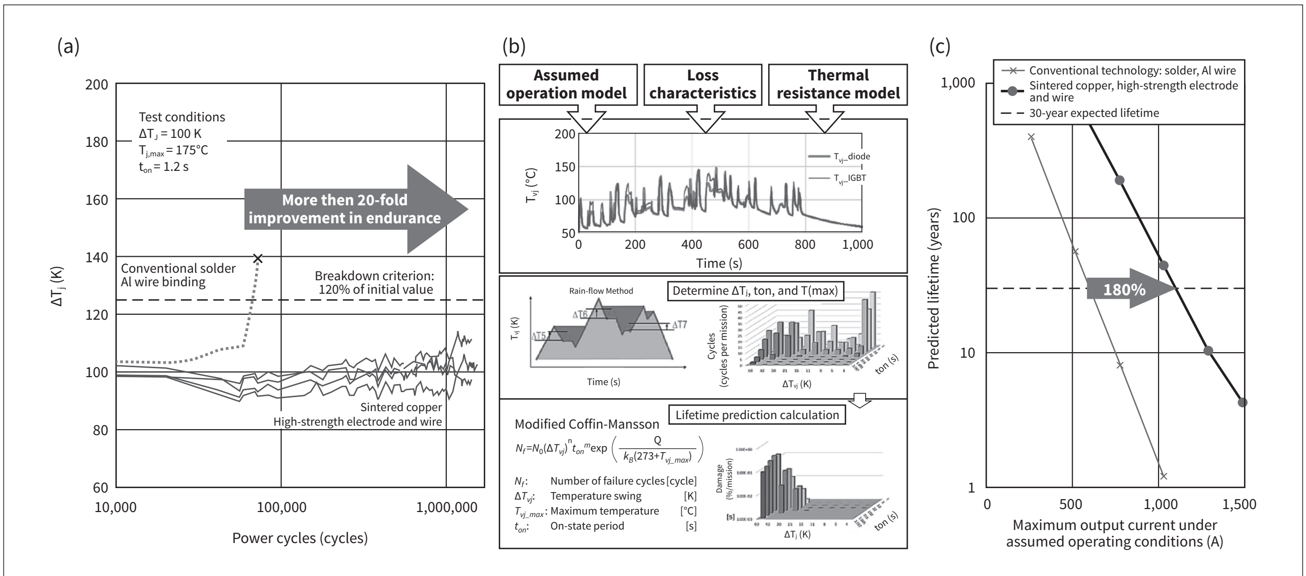


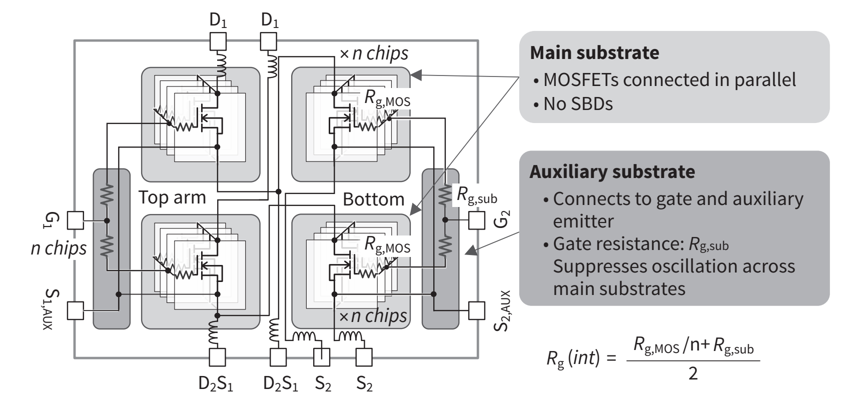
Figure 2 shows the results of device testing. At more than 1.5 million cycles, the power cycling lifetime is more than 20 times longer than previous modules that used conventional solder and Al wire [see **Figure 2** (a)], thereby satisfying the one-million-cycle lifetime requirement of Roll2Rail. Using the formula for power cycling lifetime, a lifetime prediction simulation was also performed based on the mission profile of 1,500-V_{DC}/two-level metro rolling stock [see **Figure 2** (b)]. The maximum output current for a 30-year expected life has been increased by 180% compared to a module with conventional solder and Al wire [see **Figure 2** (c)]. Samples of the module are currently available (part no.: MBM800GS33G2).

2. 3 Faster Switching in 3.3-kV-SiC Module

Being unipolar devices, SiC MOSFETs are capable of faster switching than Si-IGBTs and they significantly reduce switching losses(6). When higher output currents are needed, chips, sub-modules, and modules are connected in parallel. However, instability in this parallel system configuration can induce high-frequency oscillations of between several tens and a hundred MHz in the high-speed switching waveform(7). The nHPD² modules have two device pairs and use the internal gate resistance [R_g(int)] to suppress this waveform noise (see **Figure 3**). Increasing the ratio of

Figure 3 — Equivalent Circuit of Low-loss/High-capacity SiC MOSFET-nHPD²

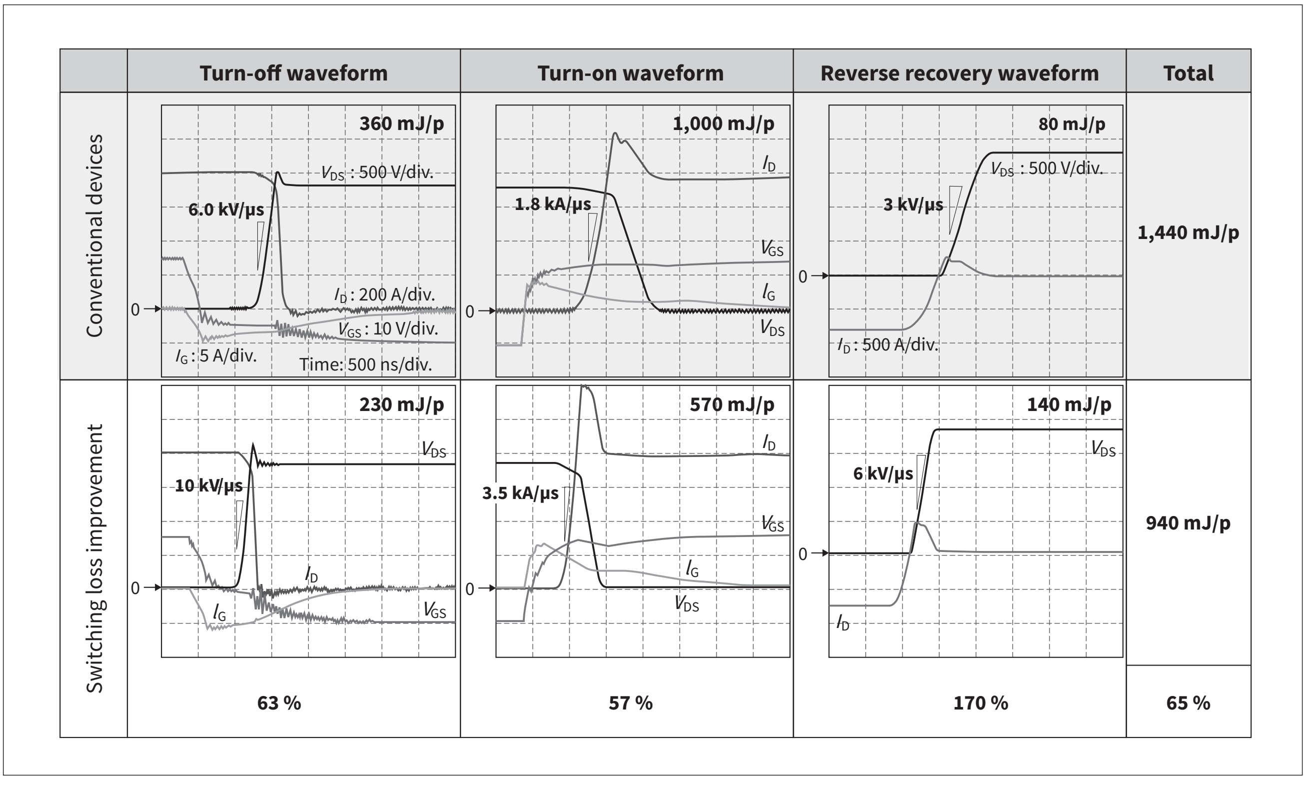
The circuit reduces the value of the R_g(int) resistance while also increasing the ratio of feedback to output capacitance and reducing the inductance across the source potentials to suppress high-frequency oscillations.



MOSFET: metal-oxide-semiconductor field-effect transistor SBD: Schottky barrier diode

Figure 4 — Comparison of Switching Waveforms for Low-loss/High-capacity SiC MOSFET-nHPD² and conventional SiC MOSFET Module

Switching losses are reduced to 65% of previous devices by reducing R_g(int) while also suppressing high-frequency oscillations.



feedback to output capacitance and reducing the inductance across the source potentials help maintain system stability. This enables R_g(int) to be reduced while still suppressing high-frequency oscillations, reducing switching losses to 65% of those of previous modules (see **Figure 4**).

2. 4 Comparison of Inverter Outputs

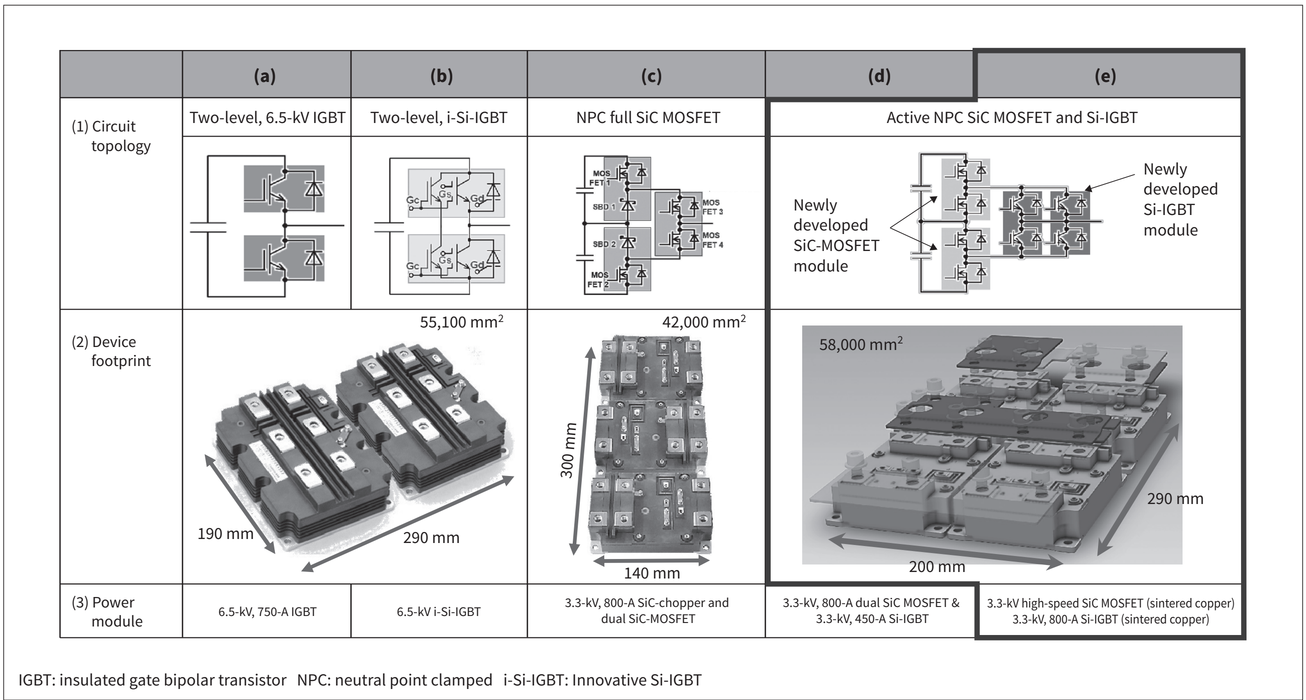
An active-neutral-point-clamped (ANPC) inverter is one example of a system that can combine the two power devices. The dependence of maximum output current on carrier wave frequency was studied for such a system.

ANPC allows for the switching frequencies of direct-current (DC) and alternating-current (AC) devices to be set independently[8]. The SiC MOSFET is used on the DC side where it can be mounted close to the DC capacitor to reduce inductance and the Si-IGBT is used on the AC load side where inductance is high. Output is maximized by using an approximate three-to-one ratio for the SiC MOSFET and Si-IGBT switching frequencies.

This was compared with a neutral-point-clamped (NPC) inverter using either 6.5-kV Si-IGBTs[9], innovative Si-IGBTs (i-Si-IGBTs)[10], or 3.3-kV SiC MOSFETs and Schottky barrier diodes (SBDs), and also with an ANPC inverter using conventional 3.3-kV Si-IGBTs and SiC MOSFETs. These are shown in columns (a) to (d), respectively, in **Figure 5**. The output current at which the bonding temperature is 15 K below the maximum rated temperature

Figure 5 — Comparison of Circuit Topologies and Devices

The diagram shows the inverter outputs for: (a) 6.5-kV Si-IGBT[9] two-level, (b) 6.5-kV i-Si-IGBT[10] two-level, (c) 3.3-kV SiC MOSFET and SBD NPC, (d) 3.3-kV Si-IGBT and SiC MOSFET ANPC, and (e) New 3.3-kV Si-IGBT and SiC MOSFET ANPC configurations.



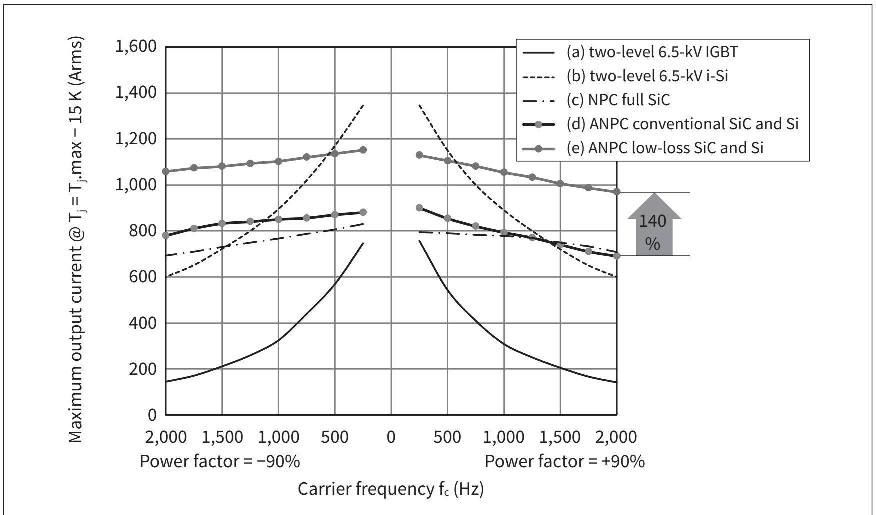


Figure 6 — Comparison of Carrier Wave Frequency Dependance of Maximum Output Current

A two-level i-Si inverter has the highest output in the low frequency range and an ANPC inverter that combines the newly developed SiC module and highly reliable Si-IGBT module has the highest output in the high frequency range.

was then determined for an inverter DC voltage of 3.6 kV_{DC}. It was also assumed that the coolant was at a temperature of 50°C and that its thermal resistance is inversely proportional to the device footprint area.

For a carrier wave in the 500-Hz-and-under range, the two-level inverter with 6.5-kV i-Si-IGBTs had the highest output. This configuration achieved more than double the output of the 6.5-kV Si-IGBTs used previously. At higher carrier frequencies, however, it was the ANPC inverter using the new power devices that had the highest output. When compared to the other ANPC inverter, the output for a 2-kHz carrier wave was 140% higher than when using the previous power devices (see **Figure 6**).

3. Conclusions

This article has compared the maximum output currents for the new power devices and their predecessors for a variety of circuit topographies. The next step is to consult with customers and calculate the maximum outputs at which the expected lifetime can be achieved for specific mission profiles. The added value over the device lifetime cycle is also determined by offsetting the difference in installation cost (including that of peripheral equipment) and the electricity running costs over a given time period against the device cost. HPSD also plans to identify the maximum cost-performance under different system operating conditions so as to offer the devices that best suit the needs of each customer.

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FEATURED ARTICLES

Nuclear Power Systems Supporting a Decarbonized Society

The accident at the Fukushima Daiichi Nuclear Power Station that occurred during the Great East Japan Earthquake has significantly altered the environment surrounding the use of nuclear power. However, in the face of the growing problem of energy security, it is still necessary to utilize nuclear power with enhanced safety to build a sustainable society while taking advantage of nuclear power's excellent characteristics, including stable energy supply, economic efficiency, and environmental suitability. These featured articles introduce Hitachi initiatives towards restarting safe and secure nuclear power generation, including the development of a fuel cycle that can contribute to the minimization of radioactive waste as well as innovative new reactors and remote-controlled robots that can operate even in high-radiation environments.

Hitachi's Work on Restarting Nuclear Power Plants

The achievement of carbon neutrality, which involves reducing carbon dioxide emissions to virtually zero as a measure against global warming, is recognized as a challenge facing the entire world. Furthermore, as energy markets are significantly destabilized due to the current international situation, the restarting of nuclear power plants as a means of dealing with these types of problems has become a priority within Japan. To contribute to carbon neutrality and the stable supply of electric power, Hitachi is strengthening its efforts towards restarting nuclear power plants while working to supply nuclear power systems that comply with new regulatory standards that offer the highest level of safety in the world. This article discusses Hitachi's efforts towards enhancing the safety of nuclear power plants before they are restarted, as well as the safety measures and construction technologies Hitachi is implementing to achieve the actual restart.

Ryusuke Kimura, P.E.Jp.
Hiroyuki Terunuma
Naohiro Fukuda

1. Introduction

As the international movement towards decarbonation proceeds with a goal of carbon neutrality, while energy markets are destabilized by Russia's invasion of Ukraine, the restarting of nuclear power plants within Japan that can contribute to the achievement of a stable supply of electricity along with carbon neutrality has become a vital domestic issue as well.

Based on the lessons learned after the Fukushima Daiichi Nuclear Power Station accident, Hitachi has formulated a basic policy for boiling water reactor (BWR) plant safety measures while promoting the development of safety enhancement technology to further increase the margin of safety at nuclear power plants.[(1), (2)] At present, to successfully restart nuclear power plants, Hitachi is supporting compliance inspections based on new regulatory standards and conducted by electric power utilities, while promoting the adoption of safety equipment by nuclear power plants.

This article describes the safety measures Hitachi has worked to develop to facilitate the restarting of nuclear power plants, as well as the safety measures and construction technologies used to quickly implement safety equipment.

2. Installation of Safety Equipment to Enable Restarting

2. 1 Overview of Safety Equipment

This section provides an overview of the design basis accident response equipment and major accident response equipment Hitachi is promoting deployment of to further improve margins of safety at nuclear power plants, which will enable them to comply with the regulatory standards necessary for restarting nuclear power plants.

In addition to the development and design of this equipment, Hitachi also uses analytical techniques such as accident progress analysis to evaluate effectiveness and confirm that the equipment can function in such a way as to maintain safety even during an accident.

(1) Design basis accident response equipment

Hitachi has installed various types of equipment to handle a wide range of design basis events [internal fire, internal overflow, external incident (earthquake, tsunami, tornado, etc.)] to maintain the safety of a nuclear power plant in the event of a design basis accident. **Table 1** shows the main enhancements adopted.

(2) Response equipment for major accidents and other incidents

Hitachi is developing safety enhancement technology and designing equipment and systems with the goal of preventing severe core damage or damage to the containment vessel even if a major accident or other such incident occurs, and is working to install this in actual facilities. **Table 2** shows the main equipment used as safety countermeasures.

2. 2 Development of Safety Enhancement Technology

This section provides the details of the safety enhancement technology that Hitachi is applying in its safety equipment.

(1) Molten debris cooling system

If molten core fuel (molten debris) damages the reactor pressure vessel during a major accident and drops to the lower part of the containment vessel, it might corrode the concrete of the containment vessel floor, causing the loss of the containment vessel's boundary function. This equipment adopts material with a high level of thermostability that, when combined with equipment that pours water into the lower part of the containment vessel, prevents molten debris from coming into contact with the containment vessel boundary, thereby serving the purpose of maintaining the boundary function.

Two representative methods developed based on the characteristics of the containment vessel type are described below.

The sump protection system[3] is a molten debris cooling system for the containment vessel structure where the sump is located in the lower part of the containment vessel. Even if molten debris falls to the floor of the containment vessel, this structure will still protect the sump from the molten debris. The floor construction system is equipment for containment vessel structures with the sump installed outside of the pedestal that supports the reactor pressure vessel. Heat-resistant material is laid on the containment vessel floor to prevent the corrosion of the floor's concrete (see **Figure 1**). With either system, the channel leading to the sump is used to detect reactor coolant leakage during ordinary operation. This channel structure utilizes a solidification evaluation model based on experimental knowledge, and is designed with a slit shape and channel area that blocks the inflow of molten debris into the sump by solidifying it within the channel.

Table 1 — Strengthening Design Basis Accident Response Equipment

The following measures are aimed at securing safety in the event of a major design basis event (earthquake, internal fire, or internal overflow).

Measure	Strengthening details
Earthquake measures	• Seismic strengthening such as construction of additional supports • Distribution of portable equipment • Confirmation of tolerance through vibration testing
Internal fire measures	• Use of fire-resistant and incombustible materials • Installation of fire detection equipment • Installation of fire extinguishing equipment • Protection of sections with fireproofing walls, etc.
Internal overflow measures	• Installation of watertight doors • Installation of weirs • Installation of leakage detectors, etc.

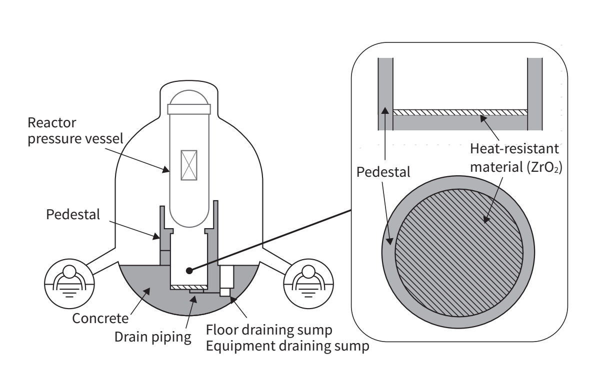
Table 2 — Overview of Equipment for Responding to Incidents Such as Major Accidents

This table lists the major safety equipment that should be introduced in the event of a major accident or similar incident to prevent major core damage and containment vessel damage, and to suppress the emission of radioactive substances.

Function	Major Safety Measure Equipment
Nuclear reactor cooling	• Alternative high-pressure water injection equipment • Alternative low-pressure water injection equipment • Decompression function enhancement equipment, etc.
Containment vessel damage prevention	• Containment vessel spraying equipment • Alternative nuclear reactor accessory cooling water equipment • Filter venting equipment • Water injection equipment in lower part of containment vessel • Molten debris cooling equipment, etc.
Damage prevention for nuclear reactor building, etc.	• Nuclear reactor building hydrotreating equipment • Hydrogen density monitoring equipment, etc.
Reduction of operator exposure	• Blow-out panel closing device, etc.

Figure 1 — Schematic Diagram of Molten Debris Cooling Equipment (Floor Construction System)

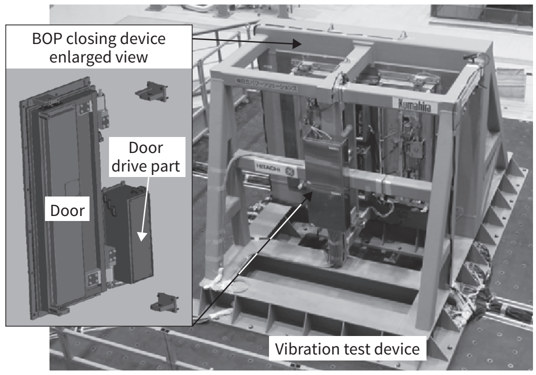
The containment vessel boundary is protected from molten debris through the adoption of heat-resistant material (ZrO_2) combined with the use of water injection equipment in the lower part of the containment vessel.



ZrO_2: zirconium dioxide

Figure 3 — Vibration Test of Side-opening BOP Closing Device

Retention of earthquake proof functionality was confirmed using a full-scale vibration test set with vibrating conditions far in excess of those that occurred during the Great East Japan Earthquake.



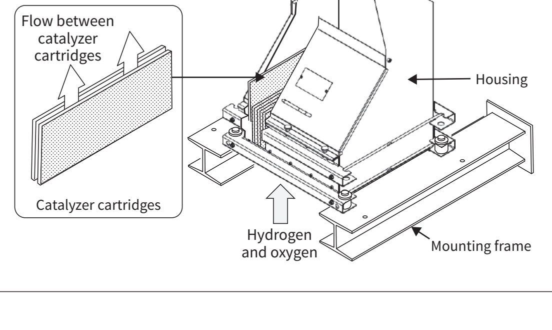
BOP: blow-out panel

(2) Hydrotreating equipment in the nuclear reactor building

Although the hydrogen gas that is generated as core damage progresses during a major accident is retained inside the containment vessel, as pressure increases inside the containment vessel, the gas may leak into the reactor building through the containment vessel's flange or other parts. One of the countermeasures to prevent leaked hydrogen from exploding inside the reactor building is the installation of a passive autocatalytic recombiner (PAR) (see **Figure 2**). A PAR is a device that recombines and passively hydrotreats combustible gas (hydrogen and oxygen gas) using a catalytic reaction, and which is designed to require no start-up operation by the operator or power supply. The locations for installing PAR devices are selected using three-dimensional flow analysis technology to identify suitable locations where sufficient hydrotreating performance can be achieved.

Figure 2 — Passive Autocatalytic Recombiner

A passive autocatalytic recombiner (PAR) is comprised of a housing and catalyzer cartridges, and causes a binding reaction in the combustible gas (hydrogen and oxygen) that flows in from the bottom due to natural circulation using each catalyzer cartridge's catalyzer (palladium) layer, in a structure that causes the resulting water vapor to be emitted from a port at the top.



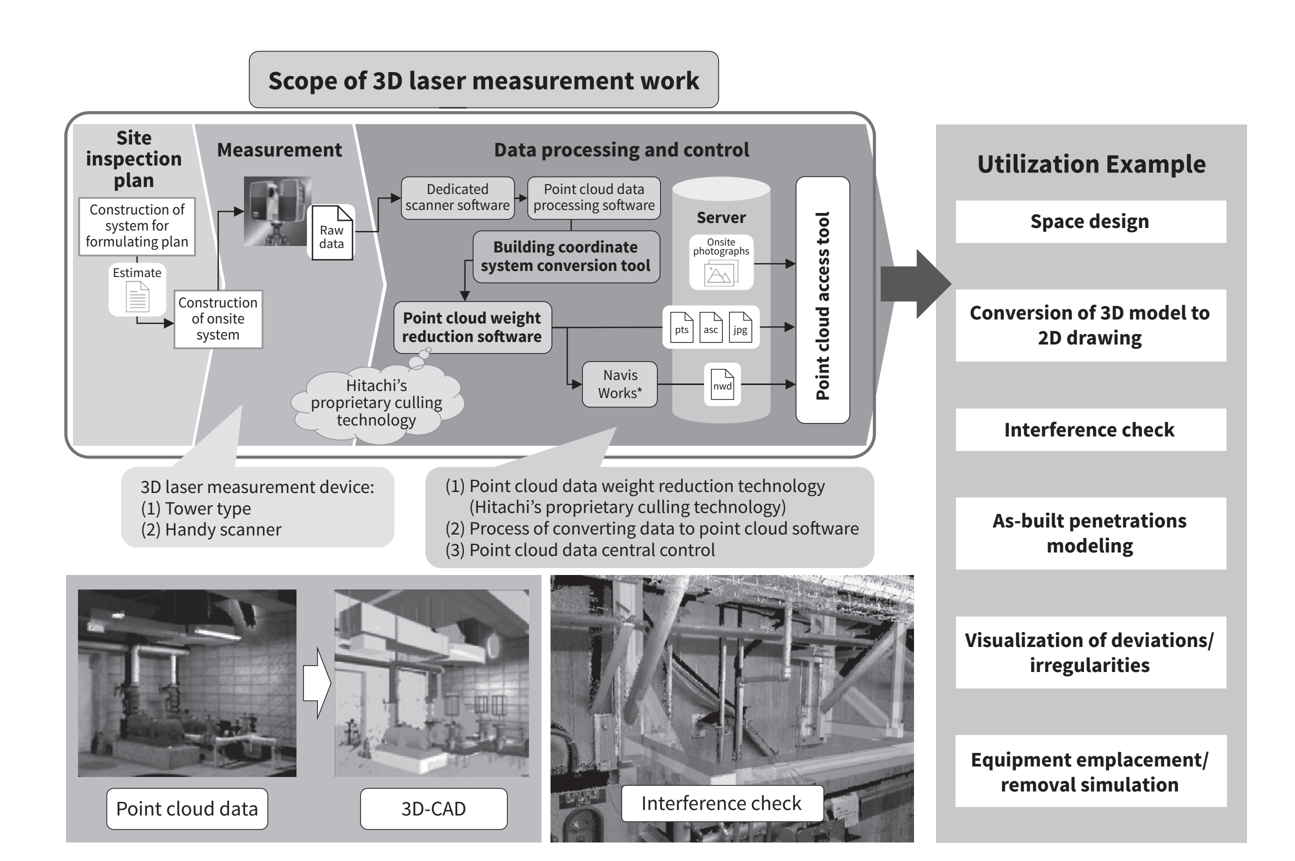
(3) Blow-out panel closing device

Blow-out panels (BOP) are installed as a pressure release mechanism to reduce pressure and temperature inside a reactor building in case of an accident at a nuclear power plant. On the other hand, the aperture part of an opened BOP may also become a conduit for the discharge of radioactive materials if a severe accident occurs. Therefore, to reduce the risk of explosion to operators during a severe accident, a BOP closing device was developed that can be closed quickly and maintains its closing functionality even during the motion caused by an earthquake.

Hitachi is developing both sliding and side-opening BOP closing devices, both can be installed according to the structure of the particular nuclear reactor building. After a BOP is opened, operators can use a mechanism to shut the BOP with an electric motor. Sliding BOP closing devices are large, motorized doors 5 m in size that can close an opened BOP using a single device. Side-opening BOP closing devices has a compact form and is designed to be suitable for use with various different BOP shapes by combining multiple devices.

Both sliding and side-opening closure devices were subjected to actual-size vibration tests in a vibration test facility, and the retention of earthquake-proof functionality was confirmed even in the case of an earthquake stronger than the Great East Japan Earthquake. Furthermore, an air leakage test was conducted after the vibration test to confirm airtightness that exceeds what is required by standards (see **Figure 3**). Also, to confirm the soundness of the side-opening BOP closing device's functionality during an accident and to improve the dependability of functions, Hitachi is confirming operations by conducting tests in a simulated environment that exposes the device to conditions such as radiation, high temperature, and high humidity.

Figure 4 — Process for Utilizing Point Cloud Data from 3D Laser Measurement Technology
By utilizing 3D laser measurement technology to collect point cloud data onsite and managing it with dedicated tools, not only is it possible to apply the technology to design work, but applications can also be expanded to construction planning and other tasks as well.



3D: three dimensional 2D: two dimensional CAD: computer-aided design
* Navisworks is a registered trademark or trademark of Autodesk, Inc. and/or its subsidiaries and/or affiliated companies in the United States and/or other countries.

3. Safety Measure Construction Technology

This section describes Hitachi's efforts towards streamlining the construction of safety measures utilizing three-dimensional (3D) laser measurement technology that it is developing as a means of quickly introducing large-scale safety equipment into nuclear power plants.

3. 1 Developing a Point Cloud Data Platform through 3D Laser Measurement Technology

Hitachi is utilizing point cloud data acquired using 3D laser measurement technology as part of nuclear power plant engineering, procurement, and construction (EPC) work to measure dimensions, produce three-dimensional computer-aided design (3D-CAD) data, and create working drawings for purposes such as constructing a new piping route onsite. To this end, Hitachi also developed a point cloud access tool to serve as infrastructure for the cross-sectional sharing of point cloud data between design departments. These tools manage multiple point cloud data formats on a centralized server while supporting the diverse usage patterns of different users with dedicated viewers and functions that link with external tools. Also, to enable users to utilize large amounts of point cloud data, the tools achieve faster processing through techniques that cull data, leaving valid data behind, and also enhance the interface. **Figure 4** shows the process for utilizing point cloud data using 3D laser measurement technology, and **Table 3** provides examples of how to utilize the data.

3. 2 Application to the Study of Streamlining Safety Measure Construction

As part of the process of preparing to restart nuclear power plants, Hitachi is proceeding with the installation of the various types of safety equipment described in the previous section in actual plants. During this safety measure construction period, it is also necessary to conduct a wide range of different conversion work in parallel, including the piping of equipment within the nuclear power plant, air conditioning, electricity, instrumentation, seismic strengthening, fireproofing, and so on. Temporary equipment used in the conversion work such as scaffolding, material storage

Table 3 — Examples of Utilizing 3D Laser Measurement Data

It is possible to utilize onsite information as point cloud data for use in a variety of different design and construction tasks.

Utilization Example	
Taking measurements for space design	Taking measurements on desktop and conducting site inspection
Converting 3D models into 2D drawings	Modeling for considering the relocation or addition of supports
Data for checking interference	Confirming interference with plan piping (CAD)
Visualization of deviations/irregularities	Measurement of complicated equipment shapes
As-built penetrations modeling	As-built display of penetration information
Simulation of equipment emplacement/removal	Interference confirmation and routing plan for transport

areas, temporary power supplies, and welding machines are also arranged around the inside of the power plant, and the layout information for locations of related equipment changes every day while construction proceeds.

To conduct this safety measure construction work safely and smoothly, it is extremely important to check for interference and plan routes according to the state of the power plant equipment so as to identify equipment that may interfere with the equipment delivery route and to formulate plans to avoid interference. Not only does this make it possible to smoothly transport equipment both in and out of the plant, but also to prevent damage to existing and newly delivered equipment due to collisions during movement.

This section introduces a study on the streamlining of a construction plan utilizing 3D laser measurement technology, based on the concrete example of an interference confirmation and routing plan for equipment loading/unloading as part of the installation of new panels.

The following six tasks must be performed to formulate an interference confirmation and routing plan before panel update construction can begin.

(1) Confirm the shape of panels to update from the drawings and specifications.

(2) Inspect the sites under consideration for the panel loading/unloading route.

(3) Identify potential obstacles and create a list of this equipment. Issue a request to the relevant design department and ask them to consider plans for avoiding interference.

(4) Inspect the sites to facilitate the relevant design department's consideration of plans for avoiding interference.

(5) Have the relevant design department create, summarize, and list interference avoidance plans based on its considerations, and reflect this in the construction plans and work drawings.

(6) If there is interfering equipment that cannot be avoided, adjust the panel specifications to enable the main panels to be brought in separately and assembled.

Since these tasks are greatly affected by backtracking work caused by situations such as when a site cannot be investigated due to other conversion work or the power plant operation plan, or by delayed confirmation of whether or not interference can be avoided, they entail a risk of drawing out the construction process. Also, since onsite inspections are mandatory, there are risks such as radiation exposure during inspections of controlled areas and construction accidents during onsite inspections.

Utilizing point cloud data from 3D laser measurement technology here enables advanced information control, and is thought to help streamline the interference confirmation and routing plan as shown in **Table 4** by shortening schedules while improving work safety. At present, the application of 3D laser measurement technology is still in the demonstration and experimentation stage, and its effectiveness as a utilized technology is being confirmed. Hitachi plans to incorporate 3D laser measurements into actual work on a trial basis in the future, and to promote further efforts towards the streamlining of safety measure construction work.

Table 4 — Effectiveness of 3D Laser Measurement Technology

Expected effects include shortening of work schedules, advanced information management, and improvements in work safety.

Shortening of work schedules	• Reduced onsite measurement work and shortened onsite inspection time • Transport routes can be simulated based on the latest information (simplifying modification and reconsideration of dimensions and routes)
Advanced information management	• By inputting removal conditions based on the onsite as-built environment (work area, removed object dimensions, truck height, and so on), it is possible to confirm the line of flow of removed objects (bird's-eye view or immersed) • Confirming subject equipment, attributes, positions, and scopes as digital data by utilizing vector data information extracted from point cloud data/CAD model/working drawings • Combined management of latest area information prevents omission during summary for interfering object countermeasure proposals
Improved work safety	• By reducing the amount of onsite work, it is possible to reduce the risk of construction disaster or exposure in the management sector • Simplifies the sharing of information related to the removal route procedures among onsite work instructors and workers

4. Conclusions

The restart of nuclear power plants is an extremely important option for securing a stable domestic supply of electric power while achieving a decarbonized society. Not only does the technology introduced in this article comply with the regulatory standards of nuclear power plants, but it can also greatly contribute to the enhancement of safety and shows promise as a way of safely and smoothly constructing safety measures.

Hitachi will continue to contribute to ensuring a stable supply of electricity and achieving carbon neutrality through its efforts to restart nuclear power plants.

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Progress on Decommissioning Fukushima Daiichi Nuclear Power Station and Use of Remotely Operated Equipment

Since the accident at the Fukushima Daiichi Nuclear Power Station that occurred during the Great East Japan Earthquake, the Hitachi Group has been developing technologies and onsite work necessary for decontamination, environmental remediation, dealing with contaminated water, removal of spent fuel, and removal of fuel debris. This article introduces the progress Hitachi is making in decommissioning the reactors at the Fukushima Daiichi Nuclear Power Station. Of the remotely operated equipment Hitachi has developed for this work, this article describes the ASTACO-SoRa dual-arm heavy machinery-type robot used for environmental remediation tasks such as debris removal, the PMORPH shape-changing robot and boat-type submersible access devices used for the internal inspection of the containment vessel carried out in order to acquire information necessary for formulating the fuel debris removal plan, and the flexible robot arm capable of heavy-duty tasks under high levels of radiation.

Satoshi Okada, Ph.D.
Hirokazu Adachi

1. Introduction

The decommissioning of the Fukushima Daiichi Nuclear Power Station has involved a wide variety of tasks inside the power station, such as decontamination, environmental remediation, dealing with contaminated water, removal of spent fuel, and removal of fuel debris. To this end, the Hitachi Group has been developing necessary technologies and proceeding with onsite work.

This article discusses the technology Hitachi has developed up to this point, the state of progress in onsite work, and key remotely operated equipment. Of the developed robots, working robots include the ASTACO-SoRa dual-arm heavy machinery-type robot that does heavy work in tight spaces, and the flexible robot arm that combines flow actuators with a spring structure while using as few electronic boards as possible to cope with high-radiation environments. Inspecting robots include the PMORPH shape-changing robot, which inspects the insides of a primary containment vessel (PCV) by entering a narrow part to reach the high-radiation area, and the boat-type submersible access device, which inspects the PCV's groundwater part. The characteristics and conditions for actual robot application are described below[1].

2. Progress on Decommissioning Fukushima Daiichi Nuclear Power Station

Hitachi is proceeding with work at the Fukushima Daiichi Nuclear Power Station that includes dealing with contaminated water, removing fuel from spent fuel pools, removing fuel debris, taking care of waste, and other reactor decommissioning tasks based on the "Mid-and-Long-Term Roadmap toward the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1-4"[2] (referred to as "the roadmap" hereinafter).

This section covers the Hitachi Group's efforts in the areas of dealing with contaminated water, removing fuel from spent fuel pools, and removing fuel debris.

2. 1
Dealing with Contaminated Water

Contaminated water is created when water is injected into a nuclear reactor to cool fuel that has melted, after the water comes into direct contact with molten fuel. It is also created when rainwater or groundwater flowing into a damaged building mixes with water containing radioactive substances that has accumulated in the underground floors of the building.

To reduce the inflow of groundwater into a building, it is necessary to draw groundwater out of wells (subdrains) located around the building's periphery to lower the water level of that groundwater, while at the same time using pumps installed inside the building to lower the water level of residual water inside the building. The Hitachi Group has contributed to the suppression of contaminated water generation by installing equipment to purify groundwater drawn from the subdrains (purification equipment for subdrains and other areas) as well as equipment for drawing water from residual water inside the building and transferring it to contaminated-water-treatment equipment (residual water transfer systems inside the building). Furthermore, by changing the positions of pumps in each building's internal residual water transfer system to the floor drain sump on the bottom floor of each building, Hitachi was able to keep the floor surface of the bottom floor exposed by implement the transfer of residual water, thereby achieving the "Complete treatment of residual water in the building within the year 2020."[*, (3)]

After Hitachi developed and installed equipment to filter, deionize, and otherwise treat water processed by contaminated water treatment equipment (high-performance polynuclear species removal equipment) to decrease radionuclides (excluding tritium) to a concentration below the notified concentration limit, and started processing operations in 2015, the plant passed a pre-use inspection in February 2023. Although the water treated by the advanced liquid processing system (ALPS) is currently stored in a tank located within the site of the Fukushima Daiichi Nuclear Power Station, there are plans to dilute it with seawater and discharge it into the ocean.

2. 2
Removal of Spent Fuel

In the Unit 4 nuclear reactor building, vent gas containing hydrogen from the Unit 3 PCV flowed in via an exhaust pipe, causing a hydrogen explosion that severely damaged the top of the building. The Hitachi Group removed piles of debris from the operation floor on the top of the building, and collaborated with Takenaka Corporation to install fuel removal covers and fuel handling equipment before removing the debris scattered within the spent fuel pool. In parallel with the task of removing debris from inside the pool, Tokyo Electric Power Company Holdings, Inc. also used fuel handling equipment to remove fuel from inside the spent fuel pool, removing 1,535 fuel rods as of the end of December 2014[(4)].

The Unit 1 nuclear reactor building lost its reactor core cooling function due to the tsunami that followed after the earthquake, and hydrogen from the damaged core leaked inside the building, resulting in a hydrogen explosion that severely damaged the top of the building. The removal of debris from the north side and center area of the operation floor on the top of the nuclear reactor building started from 2018, and the Hitachi Group completed debris fall prevention and mitigation measures by November 2020 for the debris piled up on the south side of the operation floor, including overhead cranes and fuel convertors[(5)]. The plan is to complete placement of a large cover over the entire building, after which the debris will be removed from inside the cover, and fuel handling equipment will be installed. Fuel removal by Tokyo Electric Power Company Holdings is planned to start between 2027 and 2028.

2. 3
Removal of Fuel Debris

At the time of the earthquake, fuel was stored in the reactor cores of operating units 1 to 3 and as a result of the loss of core cooling functionality due to the tsunami that followed after the earthquake, the fuel, fuel cladding tubes, structures inside the core, and other components melted. The cooled and solidified fuel debris is dispersed throughout the reactor core, the bottom of the reactor pressure vessel, and inside of the PCVs. The Hitachi Group is conducting investigations inside the PCVs to collect information pertinent to the consideration of methods to prepare for full-scale removal of the fuel debris.

During the internal inspection of the Unit 1 PCV carried out in April 2015, a PMORPH shape-changing robot was used to take images inside the PCV (aboveground part outside the pedestal) while collecting temperature and radiation dose information[(6)]. In March 2017, PMORPH-2, which has a sensor unit with attached camera and dosimeter that can be raised and lowered with a winch in place of the camera part of PMORPH-1, was used to take images inside the PCV (underground level outside the pedestal), gather dose information, and examine the spread of fuel debris[(7)].

From February 2022 to March 2023, a boat-type submersible access device was sent into the underground part of the Unit 1 PCV in order to visually examine the details inside and outside the pedestal, while producing a three-dimensional (3D) map of the underground deposits outside the pedestal and measuring thickness, detecting fuel debris, sampling deposits, and collecting information inside the PCV (inside and outside the pedestal)[(8), (9)].

* Excluding nuclear reactor building Units 1 to 3, the main process building, and buildings combusted at a high temperature.

3. Remotely Operated Equipment

To proceed with the reactor decommissioning described in previous section, the Hitachi Group has developed and utilized many types of remotely operated equipment. This section describes examples of that remotely operated equipment.

3. 1
ASTACO-SoRa Dual-Arm Heavy Machinery-Type Robot

Figure 1 shows the ASTACO-SoRa dual-arm heavy machinery-type robot that the Hitachi Group has been developing and applying for nuclear disaster response[10]. This robot features two arms on a compact chassis with a width of 980 mm, and enables a high level of freedom for working within the building. Also, the two arms can be raised to a height of approximately 2.5 m, and can lift 150 kg per arm, for a total weight of 300 kg. Furthermore, the ends of the arms can have grippers, cutting tools, rotating tools, long arms with cameras, and other parts that can be attached or detached to enable a wide range of tasks. By developing ASTACO-SoRa, the Hitachi Group has made it possible to use remote operations to remove concrete fragments and other debris from the high-radiation environment of the Fukushima Daiichi Nuclear Power Station.

3. 2
Flexible Robot Arm

The Hitachi Group has developed a “flexible robot” that avoids the use of sensors with low radiation resistance to enable use in a high-radiation environment. It combines an elastic structure with hydraulic cylinders and springs to deal with the risk of collisions during operations in a confined space so that no damage will occur even if the robot collides with another object or its surroundings[11]. **Figure 2** and **Figure 3** show examples of operations by representative flexible four-legged robot arm and dual-arm types. **Figure 2** shows operations inside a PCV during mockup testing.

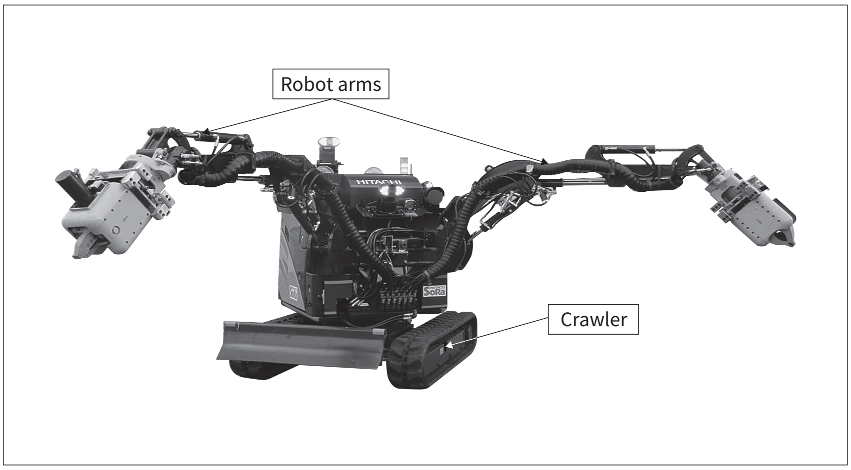


Figure 1 — ASTACO-SoRa Dual-arm Heavy Machinery-type Robot

The robot is designed for heavy-duty work inside the building, with the tools attached to the ends of the robot arms able to be swapped remotely.

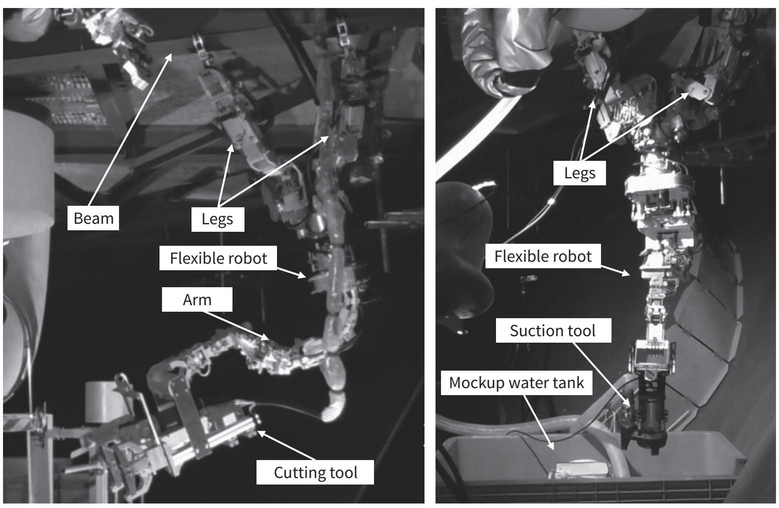
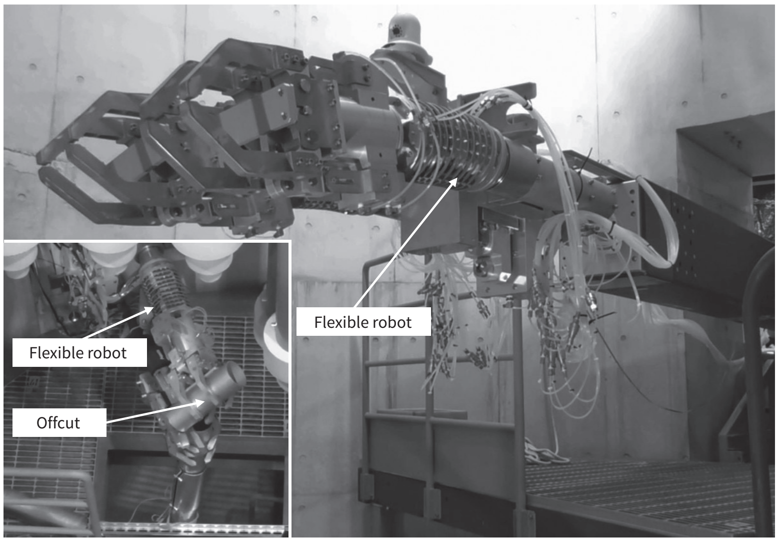


Figure 2 — Flexible Four-legged Robot Arm

The robot arm can work in any location by gripping onto grating support beams by the four legs it uses for locomotion. The robot can perform a wide variety of tasks by swapping the tools attached to the end of its arm as required. The image on the left shows a cutting tool being used to remove an obstruction. The image on the right shows the arm installing a suction tool.

Figure 3 — Flexible Dual-Arm Robot

This robot is equipped with two flexible arms. The inset on the bottom-left shows how the robot can cut an object while holding it with both arms. In this way, demolition work can proceed by removing one of the held pieces after each cut.



Capable of grabbing the beam above it and moving to any position, a single arm of the robot can be replaced with various tools, enabling it to efficiently carry out work. **Figure 3** shows a mockup test with a dual-arm type robot removing fallen objects and other materials inside a pedestal, which is a cylindrical structure that supports the reactor pressure vessel. The robots are expected to an play active role when it comes to various aspects of fuel debris removal.

3. 3 PMORPH Shape-changing Robot

Figure 4 shows PMORPH-1, which was used in a first floor grating inspection (B1 inspection) that was carried out inside the Unit 1 PCV in April 2015[12]. The image in (a) shows the shape when the robot is passing through a guide pipe, and (b) shows the shape when the robot is running over a grating while performing its inspection. PMORPH-1 includes a camera for use in inspections between the two crawlers. This camera faces forward with the robot in the shape of a C, and includes an up and down tilt mechanism that enables it to be used for visual inspection of the structural conditions inside the PCV. The robot also features a radiation dosimeter and a thermometer for use in inspecting the environment on top of the grating. This robot's investigations not only made it possible to grasp the distribution of dose rates and temperatures, but also revealed a lack of major damage to existing structures[6].

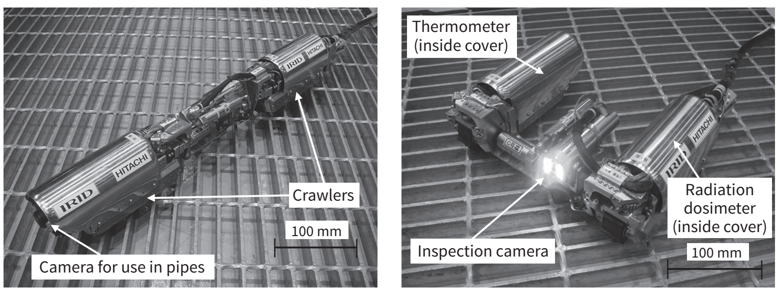
Figure 5 shows PMORPH-2, which was used to inspect the underground floor in the Unit 1 PCV (B2 inspection) in March 2017[12]. Unlike PMORPH-1, which has a camera that is used for inspections, PMORPH-2 has a mounted winch to lower the sensor unit down to the underground floor. The sensor unit itself includes a camera and a dosimeter. The inspection made it possible to grasp the state of fallen objects and deposits underground, and clearly showed how the dose rate increases closer to the floor surface[7].

3. 4 Boat-type Submersible Access Devices

Since the bottom of the PCV and underground floor in the nuclear reactor building still contain fuel cooling water and groundwater due to the accident, the Hitachi Group

Figure 4 — PMORPH-1 Shape-changing Robot

The robot can switch between two configurations for travelling through pipes and across flat surfaces respectively, thereby providing reliable ways for it to travel under different conditions.

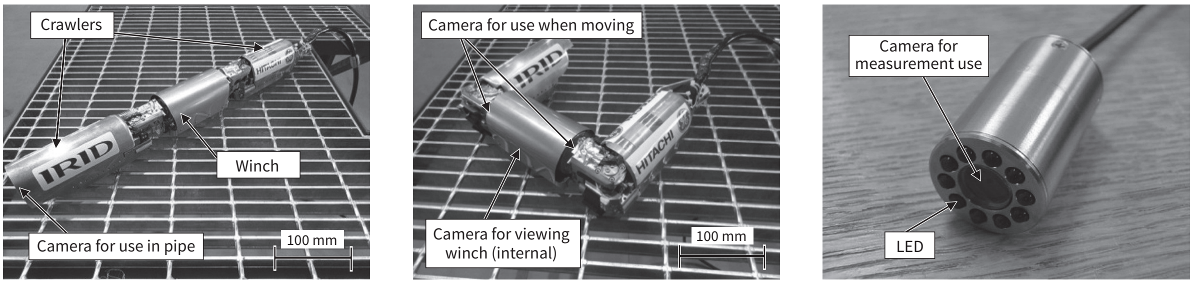


(a) Configuration for travelling through pipes (I shape)

(b) Configuration for travelling across flat surfaces (U shape)

Figure 5 — PMORPH-2 Shape-changing Robot

The survey scope was expanded by fitting a winch equipped with a sensor unit to the moving mechanism of the PMORPH-1.



(a) Configuration for travelling through pipes (I shape) (b) Configuration for travelling across flat surfaces (U shape) (c) Sensor unit detail

LED: light-emitting diode

Figure 6 — Lineup of Boat-type Submersible Access Devices

These boat-type submersible access devices can swim in the water while acquiring information regarding underground deposits with a variety of different measurement instruments. The device shown in (a) has a guide ring attached to guide cables while all ROVs navigate. Device (b) is a compact type for use in visual inspections that features enhanced mobility. Devices (c), (d), (e), and (f) have the functions of 3D mapping of deposits using ultrasound, measurement of deposit thickness using ultrasound, detecting fuel debris with a radiation detector, and sampling deposits, respectively.

(a) For attaching guide ring (ROV-A) (b) For visual inspection of a wide area (ROV-A2) (c) For mapping deposits in 3D (ROV-B)

(d) For measuring deposit thickness (ROV-C) (e) For detecting fuel debris (ROV-D) (f) For sampling deposits (ROV-E)

ROV: remotely operated vehicle 3D: three dimensional

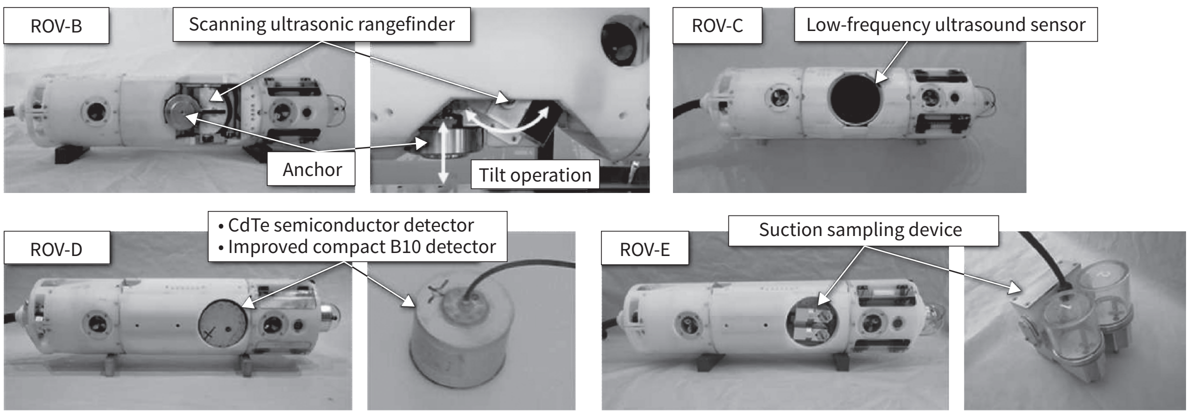
developed boat-type submersible access devices to investigate the outside of the pedestal in the underground floor within the PCV[8]. These devices are shown in **Figure 6**. The Hitachi Group has developed a total of six different remotely operated vehicles (ROVs), including five boat-type submersible access devices and one compact boat. ROV-A includes a function whereby it uses a guide ring to attach to underground structures with magnetism to prevent cables from being tangled on existing equipment. ROV-B includes a 3D deposit mapping function, ROV-C measures deposit thickness, ROV-D detects fuel debris, and ROV-E samples deposits. ROV-A2 is a compact boat device that enables the visual inspection of a wide area.

Figure 6 shows the lineup of ROV devices. ROV-B includes a scanning ultrasonic rangefinder and a water thermometer to map deposits in 3D, and is a device that acquires point cloud data from a wide area on the surface of deposits outside the pedestal. The ROV's orientation is stabilized with anchors attached to the central base of the device, and the approximately 2-MHz ultrasonic rangefinder performs

Figure 7 — Various Measurement Instruments included on Boat-type Submersible Access Devices

The boat-type submersible access devices acquire information regarding underground deposits with various types of measurement instruments that can be used while swimming underwater. Functions include the 3D mapping of deposits using ultrasound, the measurement of deposit thickness, the detection of fuel debris, and the sampling of deposits.

Inspection device	Measurement instruments	Implementation details
ROV-B 3D mapping of deposits	• Scanning ultrasonic rangefinder • Water thermometer	The scanning ultrasonic rangefinder is used to confirm height distribution of deposits
ROV-C Measurement of deposit thickness	• Low-frequency ultrasound sensor • Water thermometer	The low-frequency ultrasound sensor is used to measure the height of deposits and the state of objects underneath, and to measure the height and distribution of debris
ROV-D Detection of fuel debris	• CdTe semiconductor detector • Improved compact B10 detector	The fuel debris detection sensor is dropped onto the surface of deposits, and nuclide analysis and neutron flux measurements are used to confirm the components in the debris
ROV-E Sampling of deposits	• Suction sampling device	The deposit sampling device is dropped onto the surface of the deposits and takes samples
Maximum navigation time: approximately 80 hours/device. Since it navigates with delicate movements for the sake of inspection, a soft polyvinylchloride cable was adopted (ROV-B: φ33 mm, ROV-C: φ30 mm, ROV-D: φ30 mm, ROV-E: φ30 mm).		



two-dimensional scanning by combining mechanical scanning of ±50° using a mechanical tilting mechanism with electronic scanning of ±50° orthogonally to the tilt direction, thereby achieving three-dimensional shape measurement.

In addition, ROV-C uses an approximately 100-kHz low-frequency ultrasound sensor to measure the thickness of deposits outside the pedestal along with the height of the floor and fuel debris (a layer of chunks and powder with a high specific gravity) under the deposits.

ROV-D inspects the radiation particular to fuel debris, and includes radiation measuring instruments that can measure gamma rays to conduct nuclide analysis even under a radiation environment in excess of 10 Gy/h, while at the same time measuring neutron flux.

ROV-E uses a cylindrical sampling container with a diameter of approximately 60 mm, and includes a mechanism that samples small amounts of deposits (see **Figure 7**).

As a result of the inspections, the Hitachi Group successfully collected information pertaining to the formulation of a fuel debris removal plan, including how deposits have spread inside the PCV (inside and outside the pedestal), the state of radiation emissions, and so on.

4. Conclusions

This article has described development work that the Hitachi Group has conducted up until this point as well as onsite progress in the Fukushima Daiichi Nuclear Power Station decommissioning project, including the main remotely operated equipment.

In terms of the state of progress, it covered countermeasures for dealing with contaminated water, the removal of fuel from the spent fuel pool, and the removal of fuel debris. It has also described the remotely operated equipment, including the ASTACO-SoRa dual-arm heavy machinery-type robot, flexible robot arms, PMORPH shape-changing robots, and boat-type submersible access devices, which can be used for a wide range of inspection activities underwater.

The Hitachi Group believes that these robots have successfully contributed to progress in decommissioning work, and will continue to develop technologies for use in decommissioning work over the long term.

Acknowledgements

The devices described in this article utilize robot technology developed by the Hitachi Group. Of these devices, the PMORPH shape-changing robots and boat-type submersible access devices were developed based on subsidies from the Agency for Natural Resources and Energy, including the FY2012 grants for the development of technologies for dealing with accidents at nuclear power reactors and other such facilities, FY2013 grants for the Technology Development Project of Decommissioning and Safety Technology, FY2013 to FY2018 supplementary budgets for the Project of Decommissioning and Contaminated Water Management, and others. The dual-arm flexible robots for use in operations inside a pedestal were developed as a project of the International Research Institute for Nuclear Decommissioning, with funding from the FY2016 supplementary budget for the Project of Decommissioning and Contaminated Water Management. In addition, the development of the ASTACO-SoRa dual-arm heavy machinery-type robot utilized technological know-how cultivated from the "Project for Strategic Development of Advanced Robotics Elemental Technologies," which was commissioned by the New Energy and Industrial Technology Development Organization (NEDO) and carried out between FY2006 and FY2010. The authors would like to express their deepest gratitude to everyone involved.

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Development of Nuclear Fuel Cycle for Maximizing Resource Use and Minimizing Radioactive Waste

As Japan strives to achieve carbon neutrality by the year 2050, in addition to the use of renewable energy, there is a demand to use nuclear power to the maximum extent possible over the long term to supply electric power. For this purpose, it is necessary to achieve both effective utilization of plutonium resources and the disposal of radioactive waste, and fast reactor fuel cycle technology contributes to this through the reduction in volume and toxicity of high-level radioactive wastes and maximization of resource use. In order to achieve early demonstration of a fast reactor fuel cycle, Hitachi-GE Nuclear Energy, Ltd. is moving forward with the development of PRISM and metal fuel cycle technologies. By adopting the use of metal fuel, the PRISM offers inherent safety while at the same time providing passive safety through the use of air cooling, natural circulation, and passive components. By combining the PRISM with the metal fuel cycle, it is possible to reduce the volume and toxicity of high-level radioactive wastes while at the same time offering a high level of nuclear proliferation resistance.

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Kazuhiko Matsumura
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1. Introduction

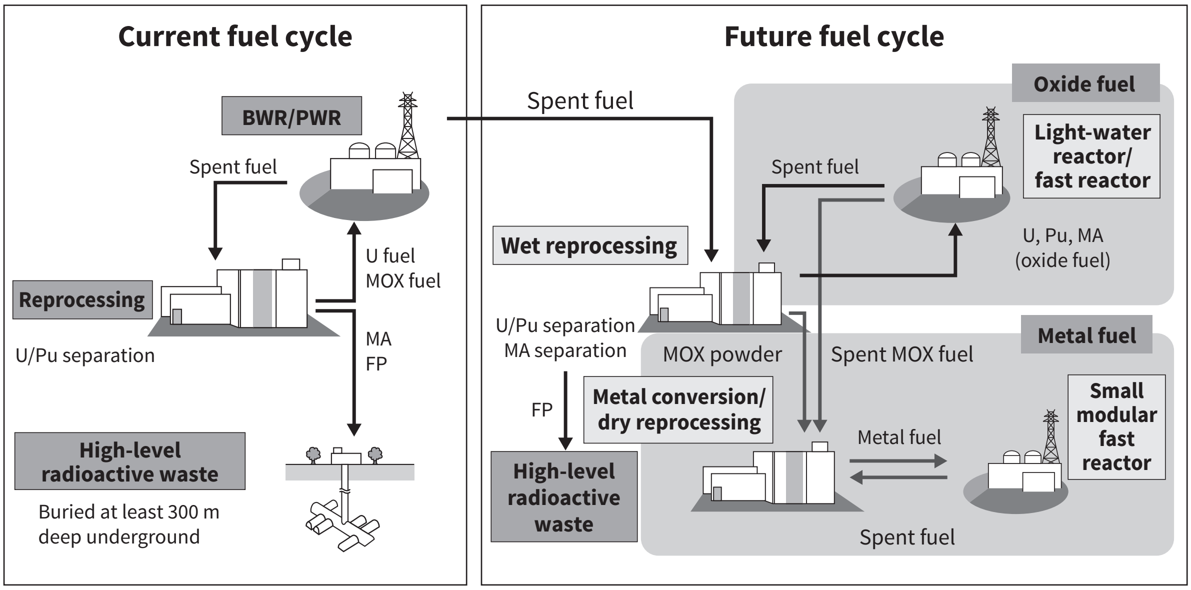
To help Japan achieve carbon neutrality by the year 2050, not only renewable energy, but also nuclear power needs to be utilized over the long term. **Figure 1** shows the current fuel cycle as well as the fuel cycle to aim for in the future to achieve a reduction in volume and toxicity of high-level radioactive wastes and maximize resource use. The high-level radioactive waste generated from the reprocessing of spent fuel includes minor actinides (MAs) that continue to retain their radioactivity and pyrogenicity. In a future fuel cycle, it will be possible to recover MAs from high-level radioactive waste and burn it as fuel in a fast reactor to reduce the radioactivity and heat quantity of high-level radioactive waste, thereby reducing the burden placed on disposal sites. Hitachi-GE Nuclear Energy, Ltd. is working toward early realization of this fast reactor fuel cycle of the future by developing technologies for the power reactor innovative small module (PRISM) and the metal fuel cycle.

In the USA, the PRISM concept has been adopted by the versatile test reactor (VTR) program, as well as by the Advanced Reactor Demonstration Program (ARDP), which is a collaboration between GE Hitachi Nuclear Energy (GE Hitachi) and TerraPower, LLC to build the Natrium* nuclear reactor. ARDP plans to start operations in the USA with the Natrium around the year 2030. Utilizing this track record of designing and building these advanced fast reactors, it will be possible to proceed with development towards a goal of introducing them domestically while demonstrating fast reactor fuel cycle technology at an early stage. PRISM can be demonstrated at an early stage in this

*Natrium is a trademark of TerraPower, LLC.

Figure 1 — Current Fuel Cycle and Fuel Cycle to Aim for in the Future

Hitachi-GE Nuclear Energy is working toward the early realization of the fast reactor fuel cycle of the future by developing the power reactor innovative small module (PRISM), an innovative small modular sodium-cooled reactor, as well as technology for the metal fuel cycle.



BWR: boiling water reactor PWR: pressurized water reactor MOX: mixed oxide MA: minor actinides [neptunium (Np), americium (Am), curium (Cm), etc.]
FP: fission products (substances created by nuclear fission) U: uranium Pu: plutonium

way, and can be flexibly expanded to support the necessary scale while providing value in the areas described below.

(1) As shown in **Figure 1**, spent fuel generated in a light-water reactor is reprocessed, the recovered mixed oxide (MOX) powder is converted to metal, and the metal fuel is supplied to the PRISM as new fuel. Additionally, spent fuel generated in PRISM is treated using dry reprocessing and converted to metal, and the metal fuel is supplied to the PRISM as new fuel. This makes it possible to utilize the current light-water reactor fuel cycle while achieving a fast reactor fuel cycle. This combination of a PRISM reactor and small-cycle pyro-reprocessing of metallic fuel will enable the reduction of installation costs and early demonstration of the fast reactor fuel cycle. In addition, utilizing this prior track record in the USA and USA-Japan cooperation will reduce development costs in Japan and accelerate development.

(2) Since, in principle, the pyro-reprocessing of metallic fuel recovers uranium (U) and plutonium (Pu) along with the MAs, the MA burning cycle can be completed on a small scale, making it possible to demonstrate MA combustion at an early stage. This characteristic also provides the benefit of a high level of nuclear proliferation resistance.

(3) After demonstration is achieved, it will be possible to increase the number of reactors and cycle facilities of the same type as needed while flexibly responding to changes in fuel cycle demand.

Hitachi-GE Nuclear Energy is considering the feasibility of introducing a metal fuel fast reactor fuel cycle that is compatible with domestic oxide fuel cycles, while studying and developing scenarios that involve reducing the volume and toxicity of high-level radioactive waste by burning the MAs generated in the oxide fuel cycle in a metal fuel fast reactor.

This article describes the state of this development work.

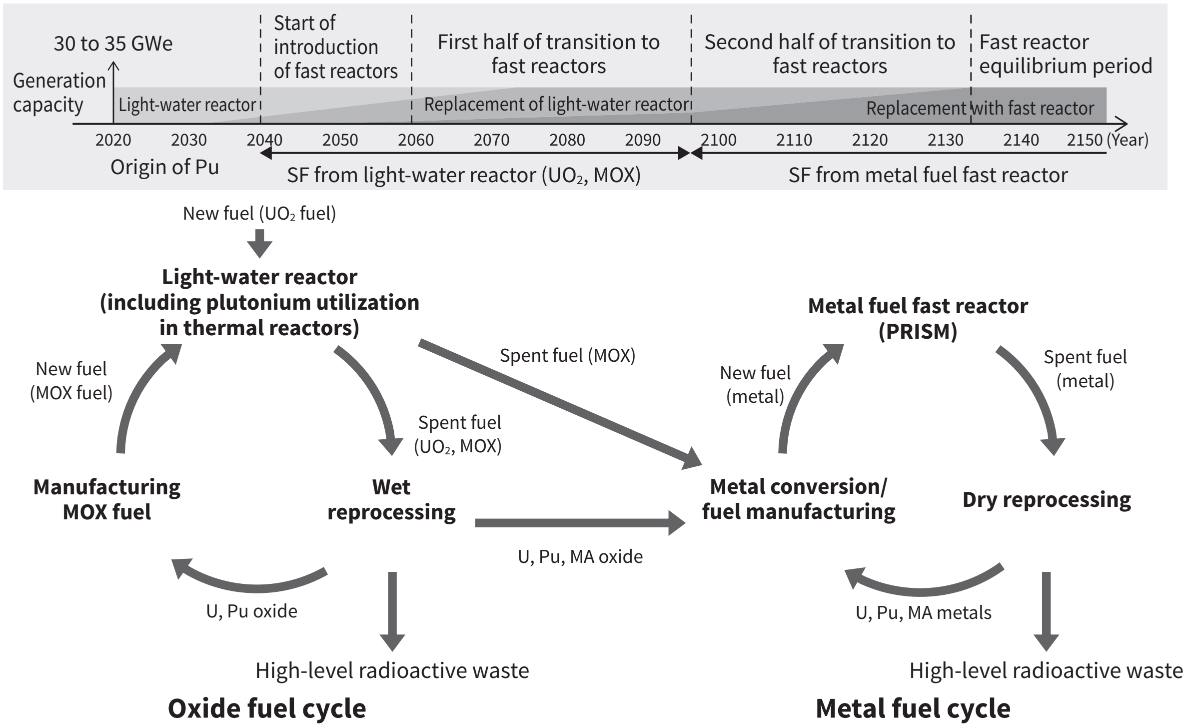
2. Domestic Introduction of PRISM and the Metal Fuel Cycle

Hitachi-GE Nuclear Energy is considering scenarios for the introduction of the PRISM and the metal fuel cycle in Japan. The current light-water reactor fuel cycle is comprised of the oxide fuel cycle, which includes the oxide fuel reactor core, oxide fuel manufacturing, and wet reprocessing, and the introduction of the PRISM and its use of metal fuel, along with its metal fuel cycle, must be rationally and efficiently implemented in a way that conforms with domestic nuclear fuel cycle policies. **Figure 2** shows the oxide fuel cycle and the metal fuel cycle.

The U, Pu, and MA oxides recovered in the oxide fuel cycle are converted to metals that are burned in a metal fuel fast reactor. Dry reprocessing technology with a high level of nuclear proliferation resistance is used to reprocess the spent fuel generated in a metal fuel fast reactor. Fast reactors, which consume fissile materials as fuel by using fast neutrons, have the potential to achieve high breeding ratios, and have a high level of flexibility with respect to fuel composition. For the future fuel cycle, in addition to

Figure 2 — Domestic Introduction of Metal Fuel Cycle

Hitachi-GE Nuclear Energy is considering the domestic introduction of the PRISM. The MAs generated by the oxide fuel cycle are burned in the metal fuel cycle to reduce the volume and toxicity of high-level radioactive wastes.



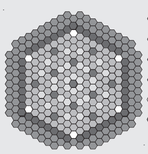
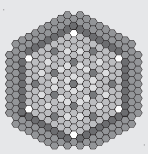
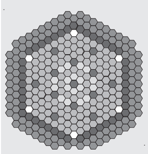
SF: spent fuel UO_2: uranium dioxide

multi-recycling using metal fuel, the spent MOX fuel that will be generated through future plutonium utilization in thermal reactors will be used as raw material for metal conversion and dry reprocessing, after which the results will be used as metal fuel with the goal of reducing the accumulation of spent fuel. Also, since U, Pu, and MA are recovered simultaneously during dry reprocessing, by combining a metal fuel fast reactor with dry reprocessing it will be possible to reduce the toxicity of high-level radioactive waste.

3. PRISM Reactor Core Configurations and Introduction Scenarios for the Domestic Introduction

Figure 3 — Reactor Core Configurations According to Introduction Period

The reactor core is configured based on the composition of the spent fuel that serves as raw material for the metal fuel, whether or not there are MAs, and the introduction period scenario. As the Pu residual ratio (the ratio between Pu amounts before and after burning) is > 1, Pu breeding and effective resource utilization are possible.

Introduction period	2040 (first unit)	2060 and after	2080 and after
Loaded fuel	• Originating from MOX powder (recovered materials from reprocessing spent UO_2 fuel) • PuF (fissile Pu) ratio: high	• Originating from MOX powder, with MAs (materials recovered from reprocessing spent UO_2 fuel) • PuF ratio: high	• Originating from spent MOX fuel for plutonium thermal use, with MAs • PuF ratio: low
Reactor core configuration/ fuel rods	**Reactor core A**  Core fuel 120 Internal blanket 30 Radial direction blanket 45 Control rods, etc. 13 GEM 6 Reflector + shield 177	**Reactor core D**  Core fuel 120 Internal blanket 30 Radial direction blanket 45 Control rods, etc. 13 GEM 6 Reflector + shield 177	**Reactor core B**  Core fuel 132 Internal blanket 18 Radial direction blanket 45 Control rods, etc. 13 GEM 6 Reflector + shield 177
Breeding	• Pu residual ratio 1.06	• Pu residual ratio 1.05	• Pu residual ratio 1.01

GEM: gas expansion module

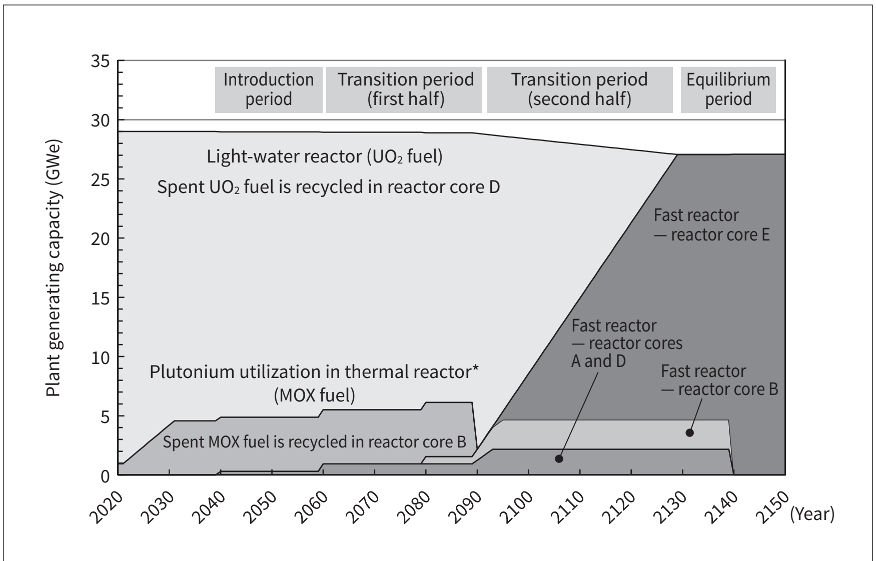


Figure 4 — Power Plant Capacity after Domestic Introduction of PRISM

Generation capacity is set for each reactor core based on a consideration of the balance between accumulated spent fuel and Pu, and the raw materials for metal fuel.

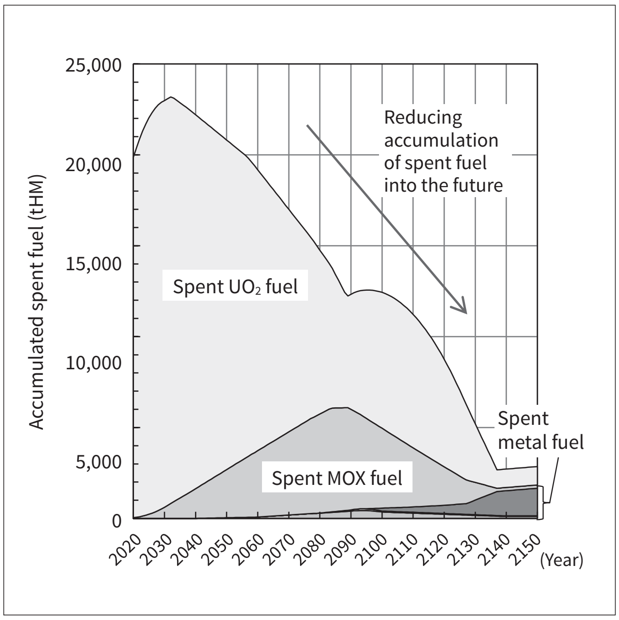
In the domestic introduction of the metal fuel cycle based on the PRISM, Hitachi-GE Nuclear Energy is considering multiple fast reactor cores based on the ratio of fissile plutonium (PuF) in the Pu of spent fuel produced domestically. To construct transition scenarios to the fast reactor equilibrium cycle, the company considered multiple fast reactor core introduction paces and the feasibility and effectiveness of domestic introduction.

Envisioning a gradual transition from light-water reactors to fast reactors, Hitachi-GE Nuclear Energy is considering scenarios involving the introduction of metal fuel fast reactors that conform to the oxide fuel cycle. **Figure 3** shows the characteristics of reactor core A, which uses metal fuel with MOX as raw materials made from reprocessed and recovered spent fuel from domestic light-water reactors, reactor core D, which uses metal fuel including MAs, and reactor core B, which uses metal fuel with spent MOX fuel as raw materials. For any of these cores, the Pu residual ratio (ratio of the amount of Pu before and after burning) is 1 or higher, which means that the prospects are good for sustainability in the effective utilization of resources through Pu breeding.

Nuclear power plant capacity and the pace of introduction for fast reactors were set based on a consideration of factors such as the Strategic Energy Plan[(1)]. Core specifications for light-water reactors and thermal reactors utilizing plutonium were set while referring to bibliographical values, etc.[(2)] **Figure 4** shows the results of evaluating the pace of fast reactor introduction. The thinking concerning the pace of fast reactor introduction envisions the introduction of the first unit in 2040, followed by halting plutonium utilization in thermal reactors in 2090 or later, and replacing light-water reactors with fast reactors. **Figure 5** shows the accumulation of spent fuel, as evaluated based on these domestic introduction scenarios. Since the accumulation

Figure 5 — Progress of Accumulation of Spent Fuel

It is possible to supply the necessary amount of Pu for introducing fast reactors from domestic spent fuel.

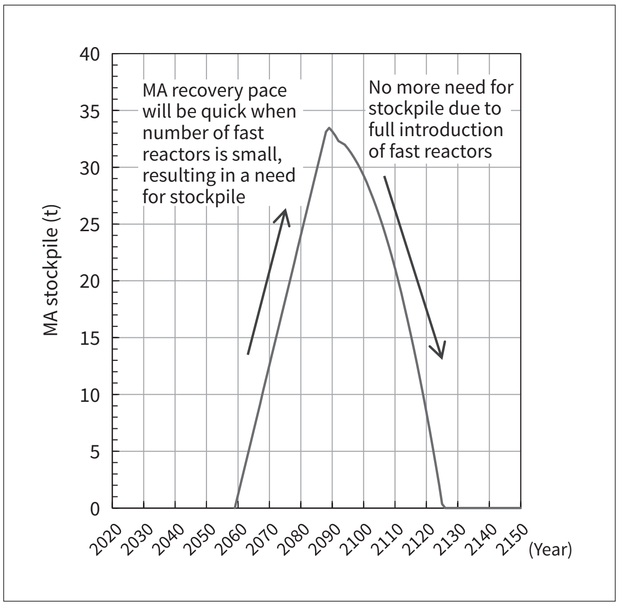


of spent fuel does not become a negative value, this means the outlook is good for securing the necessary amount of Pu from domestic spent fuel until the equilibrium period for the domestic introduction of the PRISM, and this indicates feasibility for the domestic introduction of the PRISM from the viewpoint of Pu balance. The plan is to continue studying domestic introduction scenarios while considering Pu balance based on the latest information.

MAs that are radionuclides with a long half-life will need to be burned in order to reduce the volume and toxicity of high-level radioactive wastes. PRISM is a fast reactor that can burn MAs, and so if a metal fuel has an MA concentration of up to around 5%, it is thought to be feasible for use

Figure 6 — Progress of MA Stockpiles in Domestic Introduction Scenarios

Although the MA stockpile will gradually increase during the fast reactor introduction period, it is projected that the MA stockpile will be eliminated at the time of full introduction due to the fuel load.



as a fuel due to the wealth of experimental information that has been accumulated. Also, dry reprocessing using molten salt electrolysis can recover MAs along with Pu, and past testing results evaluated the MA recovery rate at approximately 99.5%. **Figure 6** shows the result of evaluating MA stockpiles based on the balance of MA recovery amounts and supplies of MA metal fuel in domestic introduction scenarios. While the number of fast reactors introduced is still low, since the pace of recovering MAs through wet reprocessing is faster, a temporary MA stockpile will be necessary, but as fast reactors are introduced, MAs will be gradually loaded into fuel, and it is expected that the need for an MA stockpile will diminish.

Based on the above, Hitachi-GE Nuclear Energy has successfully verified prospects for achieving the impact of the fast reactor cycle, which is the reduction in volume and toxicity of high-level radioactive wastes and maximizing resource use, through the domestic introduction of PRISM and the metal fuel cycle.

4. Conclusions

Hitachi-GE Nuclear Energy has considered the feasibility of a metal fuel fast reactor fuel cycle that conforms with domestic nuclear fuel cycle policies, and has determined that the prospects are good for compliance after domestic introduction. The company will continue working to develop small modular fast reactors and the metal fuel cycle based on these innovative technologies.

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Activities in Hitachi-GE Nuclear Energy for Development of Advanced Reactors

Hitachi-GE Nuclear Energy, Ltd. has put forward a vision for nuclear power that seeks to achieve reduced initial investment risk, reliable power supply over the long term, and lower radioactive waste toxicity. It is currently developing four new reactor designs to realize this vision: the HI-ABWR large light-water reactor, the BWRX-300 highly economical small modular light-water reactor, the RBWR light-water-cooled fast reactor, and the PRISM, which is an innovative, small modular sodium-cooled fast reactor. The HI-ABWR offers a high degree of safety through the rational implementation of equipment as countermeasures to what occurred during the Fukushima accident along with the introduction of new safety mechanisms. The BWRX-300 has been comprehensively simplified to provide both safety and economic performance. The RBWR is a fast reactor based on proven light-water cooling technology, and the PRISM combines a high level of intrinsic safety and economic performance through the adoption of innovative technologies. In the future, the company intends to continue developing technologies to provide solutions to global energy problems and to work towards the early practical implementation of these four reactor designs.

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1. Introduction

Drawing on its experience with the construction of boiling water reactors (BWR) and fuel cycle technologies, Hitachi-GE Nuclear Energy, Ltd. (Hitachi-GE) is utilizing open innovation for the joint international development of four reactor designs (see **Figure 1**). These are the highly innovative advanced BWR (HI-ABWR) large light-water reactor, the BWRX-300 highly economical small modular light-water reactor, the resource-renewable BWR (RBWR) light-water-cooled fast reactor, and the power reactor innovative small module (PRISM), which is an innovative, small modular sodium-cooled fast reactor.

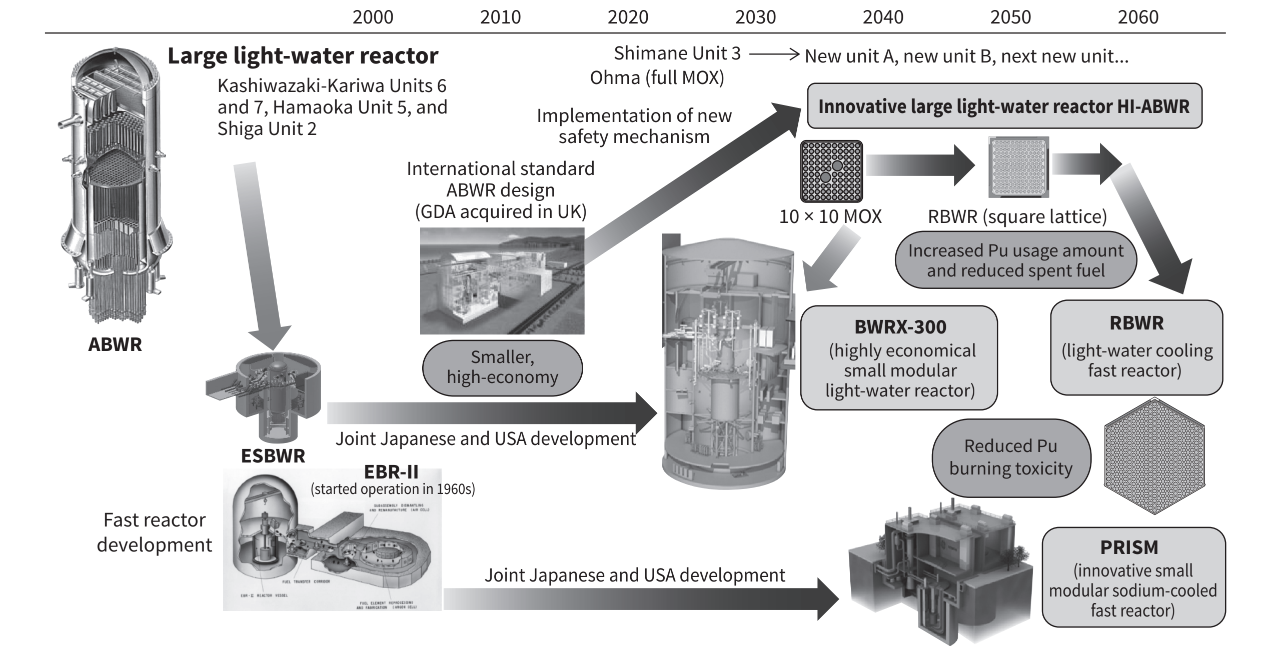
This article describes the features of these four reactor designs and the technologies that Hitachi-GE is developing to enable their practical implementation.

2. HI-ABWR Large Light-water Reactor

Various types of safety improvement measures have been implemented on nuclear reactors based on the lessons learned after the Great East Japan Earthquake and Fukushima Daiichi Nuclear Power Station accident (hereinafter, "Fukushima nuclear accident") of 2011. Hitachi-GE established the international standard ABWR design reflecting the high degree of safety in the regulatory requirements of the UK as well as the lessons of the Fukushima nuclear accident. This reactor, which is called the UK ABWR, incorporates lessons learned after the Fukushima nuclear accident with measures to suppress the occurrence of accidents (such as strengthened resistance to hazards from external incidents, safety-divisional separation barrier inside a building to handle internal incidents, and so

Figure 1 — Hitachi-GE Nuclear Energy's Nuclear Power Vision

Hitachi-GE Nuclear Energy, Ltd. is utilizing open innovation to develop new reactors through joint international development projects based on its BWR construction experience and fuel cycle technology, thereby achieving lower initial investment risk, a long-term stable power supply, and reduced radioactivity.



ABWR: Advanced boiling water reactor ESBWR: economic simplified boiling water reactor RBWR: resource-renewable boiling water reactor EBR-II: experimental breeder reactor-II PRISM: power reactor innovative small module MOX: mixed oxide GDA: Generic Design Assessment HI-ABWR: highly innovative ABWR Pu: plutonium

on), measures to ameliorate the effects of accidents (prevent core damage, etc.), and measures to handle incidents such as airplane crashes and other terrorist attacks. Following the British certification process, it received Design Acceptance Confirmation (DAC) in 2017.

The HI-ABWR further enhances the UK ABWR's resistance by implementing equipment designed as countermeasures to the Fukushima nuclear accident for natural disasters, terrorism, and internal hazards from the perspectives of safety and operability during an accident. It reduces the risk of a severe accident, while introducing new improved safety mechanisms in an innovative, large light-water reactor. **Figure 2** shows an overview of the HI-ABWR. The plan is to develop and gradually apply

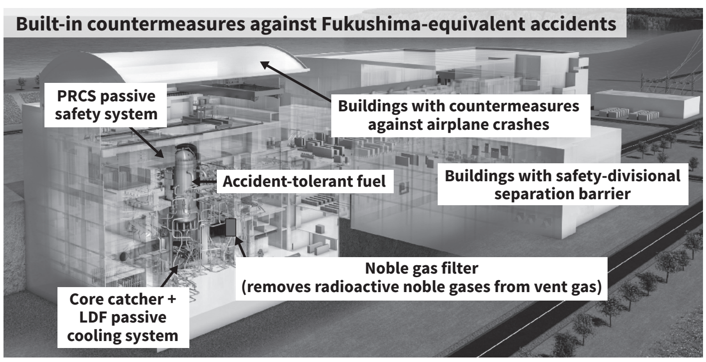
Figure 2 — Overview of HI-ABWR

The HI-ABWR is an innovative, large light-water reactor incorporating new safety mechanisms based on the standard international ABWR design, reflecting countermeasures for what occurred during the Fukushima nuclear accident as well as the requirements of UK and European regulations.

A nuclear reactor that can be accepted by people even after the Fukushima nuclear accident

(1) Innovative safety
- Safety functions protected through strengthened resistance to natural disasters, terrorism, and internal hazards
- Suppression of the expansion of an accident using natural power to activate passive safety equipment
- Compact filters to remove radioactive substances (noble gases) in order to significantly reduce impacts on the external environment during a major accident

(2) Advancement of plant functions moving towards carbon neutrality
- Flexible operations that respond to social needs by taking advantage of the characteristics of a BWR



PRCS: passive reactor cooling system LDF: lower drywell flooder improvements by introducing new equipment, including a passive reactor cooling system (PRCS) that can maintain the submergence of the reactor core using natural power to eliminate decay heat after an accident without relying on a power supply or the actions of operators, a noble gas filter that can mitigate the effects of exposure on operators and residents in case a severe accident occurs with an improved radioactive substance containment function, a core catcher that can passively cool molten debris with a debris cooling system if a core meltdown occurs, accident-tolerant fuel with stronger heat resistance that can inhibit the generation of hydrogen during an accident, and others.

3. BWRX-300 Small Modular Light-water Reactor

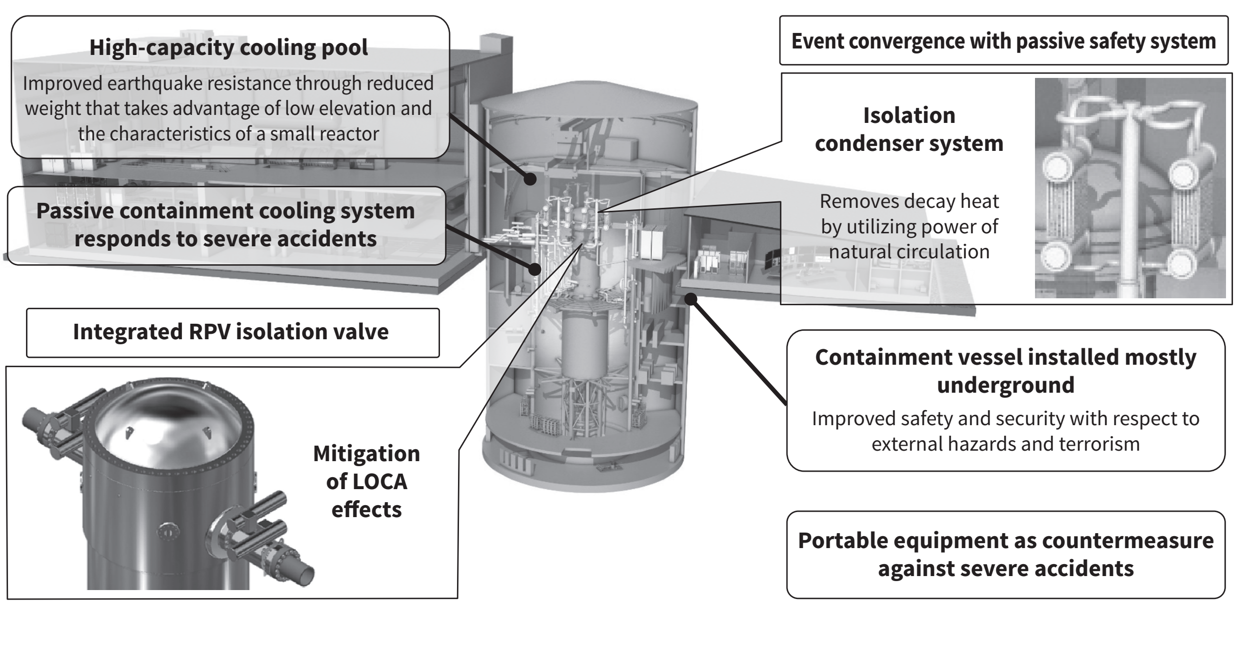
The value of nuclear power is being re-evaluated as society seeks to achieve carbon neutrality. The deregulated electric power market is looking for power plants with lower power generation costs, smaller capital costs, and reduced investment risks. Against this backdrop, small light-water reactors are drawing the world's attention. Hitachi-GE is collaborating with its US partner, GE Hitachi Nuclear Energy (GEH) to develop the BWRX-300, which is a small modular reactor based on decades of boiling water reactor experience. The BWRX-300 offers improved economic performance while maintaining a high level of safety.

Figure 3 shows an overview of the BWRX-300. In electrical production configuration, the BWRX-300 produces approximately 300-MWe using a direct steam cycle. The BWRX-300 utilizes isolation valves integrated with the reactor pressure vessel (RPV) to simplify its response to accidents, especially loss of coolant accidents (LOCAs). These integrated isolation valves along with the isolation condenser cooling system (ICS) quickly terminate coolant leaks from piping greater than 25 mm in diameter and form a closed loop cooling cycle with the steam generated in the RPV flowing to the ICS, condensing, and then returning to the RPV. This closed loop cooling cycle is automatically initiated when LOCA conditions are present or there is a loss of power. This enhances the safety of the plant while simplifying the structures, systems, and components. This simplification decreases operating and maintenance costs and decreases the amount of material that must be decommissioned at the end of plant life.

The BWRX-300 utilizes decades of experience and improvements from the BWR and ABWR fleets. Many of the components such as the RPV and reactor internals are the same as, or scaled from, the operating fleets. The fuel used in the BWRX-300 is exactly the same as the fuel used in BWRs in Europe and the USA. The BWRX-300 has 240 fuel bundles, which is the same number as a BWR in Switzerland that successfully operated for over forty years before it ceased operation in 2019.

Figure 3 — Overview of BWRX-300

Adoption of an innovative integrated RPV isolation valve ameliorates the effects of a LOCA, and passive safety system configuration allows the safety system to operate even without AC power or operator actions.



RPV: reactor pressure vessel LOCA: loss of coolant accident AC: alternating current

The BWRX-300 is enjoying commercial success in North America and Europe with prospects in many other countries. The lead BWRX-300 and three follow-on units are being deployed by Ontario Power Generation Inc. (OPG)(1) in Canada. Also in Canada, Saskatchewan Power Corporation(2) has selected the BWRX-300 for deployment in the province of Saskatchewan. The Tennessee Valley Authority electric power company is progressing with its construction permit application for a BWRX-300 at its Clinch River site in Tennessee, USA(3). Orlen Synthos Green Energy is working towards deploying multiple BWRX-300s at several sites in Poland. Fermi Energia has selected the BWRX-300 to construct in Estonia(4).

The BWRX-300 is progressing with licensing in North America and Europe. In Canada, the BWRX-300 has successfully completed a combined Phase 1 and 2 Vendor Design Review(5). The US nuclear regulator has approved five licensing topical reports related to the unique features of the BWRX-300 and two other licensing topical reports are underway. In Poland, the regulator has approved the General Opinion for the BWRX-300 and is evaluating the Decision in Principal for several sites. GEH has applied to enter the first two steps of Generic Design Assessment in the UK.

Hitachi-GE will continue participating in these projects with its US partner GEH.

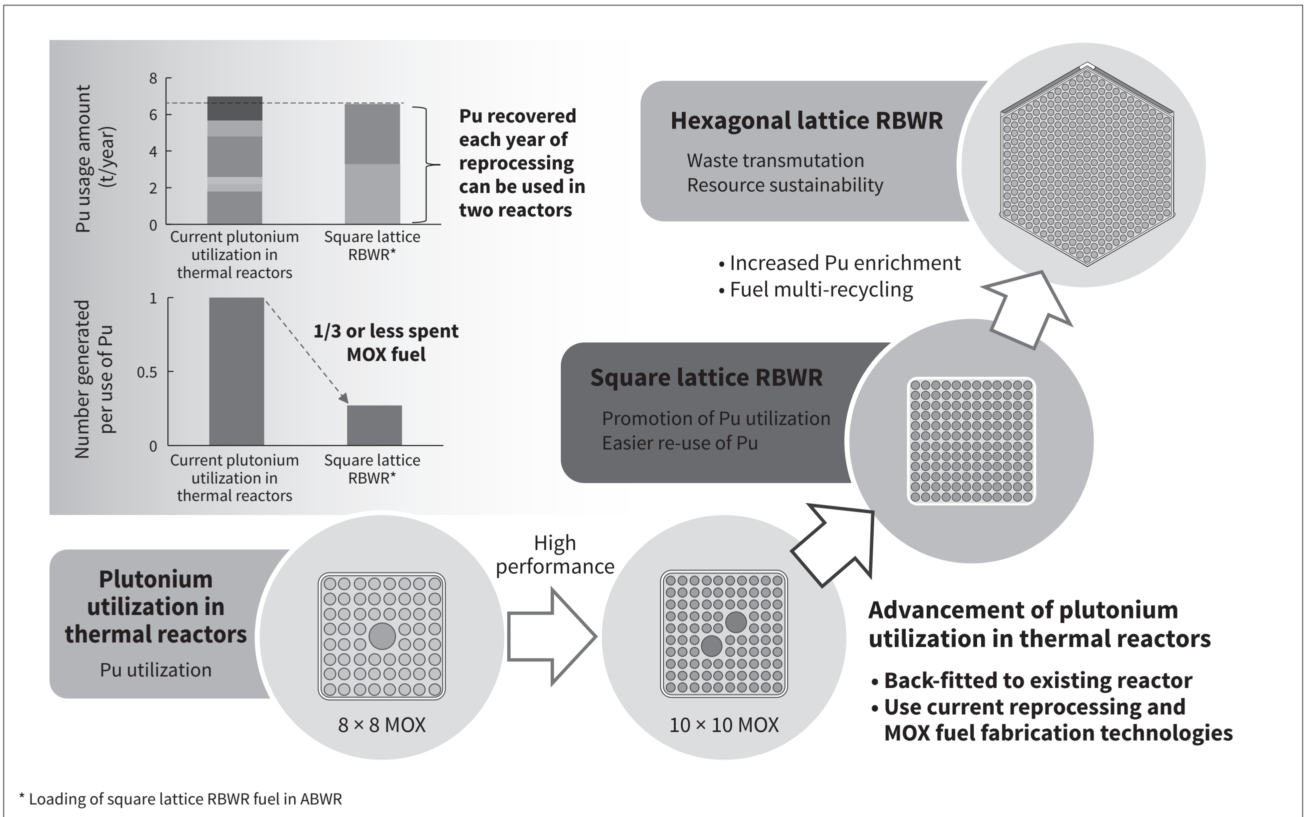
4. RBWR Light-water Cooling Fast Reactor

Hitachi-GE has worked on developing the RBWR, which takes advantage of the characteristics of the BWR by boiling the cooling water (neutron moderator). In addition to this boiling of cooling water, the RBWR uses tight-lattice fuel to decrease the water-to-fuel ratio, and the design shifts the neutron energy distribution to the high-energy side more than in the case of an ordinary light-water reactor. **Figure 4** shows the company's plans for introducing the RBWR. While working towards a final goal of a hexagonal lattice RBWR that achieves a fast reactor cycle, the company is first developing a square lattice RBWR that can be back-fitted to existing reactors to promote the utilization of reprocessing plants, which will facilitate the use of plutonium, and to reduce the volume of spent fuel to maintain the maximum possible utilization of nuclear power generation.

By increasing the plutonium load for each fuel assembly, the square lattice RBWR approximately doubles the plutonium usage amount of the current BWR plutonium utilized in thermal reactors [using mixed oxide (MOX) fuel, which mixes the uranium and plutonium recovered from uranium spent fuels for use in a light-water reactor].

Figure 4— Envisioned Introduction of RBWR

The RBWR uses fuel arranged with rods in a tight lattice in order to suppress the deceleration of neutrons via collision with cooling water and increase energy beyond that of traditional BWRs. Hitachi-GE is promoting the development of a square lattice RBWR that will accelerate the use of plutonium while contributing to a reduction in spent fuel.



From the perspective of nuclear nonproliferation, Japan's policy is to only reprocess spent uranium fuels for as much plutonium as it can recover from them for use in thermal reactors, and so, by increasing the amount of plutonium used per fuel assembly, even if the number of plants that can use plutonium is limited, it will still be possible to increase the reprocessing amount and further reduce the spent uranium fuel stockpile. Also, this increase in the plutonium load per fuel assembly decreases the number of spent MOX fuels, using the same amount of plutonium as current BWR plutonium utilization in thermal reactors.

As the decay of ^{241}Pu proceeds during the long-term storage of spent MOX fuel after plutonium utilization in thermal reactors, and since fissile plutonium is insufficient when it is re-used in a fast reactor, there may be cases where additional processing is necessary such as mixing recovered plutonium from spent uranium fuel with a comparatively high ratio of fissile plutonium. Therefore, the square lattice RBWR increases the amount of plutonium used while giving consideration to the re-use of spent MOX fuel generated in square lattice RBWRs in future fast reactors, and uses the fast neutron spectrum with tight lattice fuel to maintain an even higher ratio of fissile plutonium than current plutonium utilization in thermal reactors. The plan is to use this method to reduce the amounts of spent fuel that need to be stored and reprocessed for the transition to the fast reactor cycle.

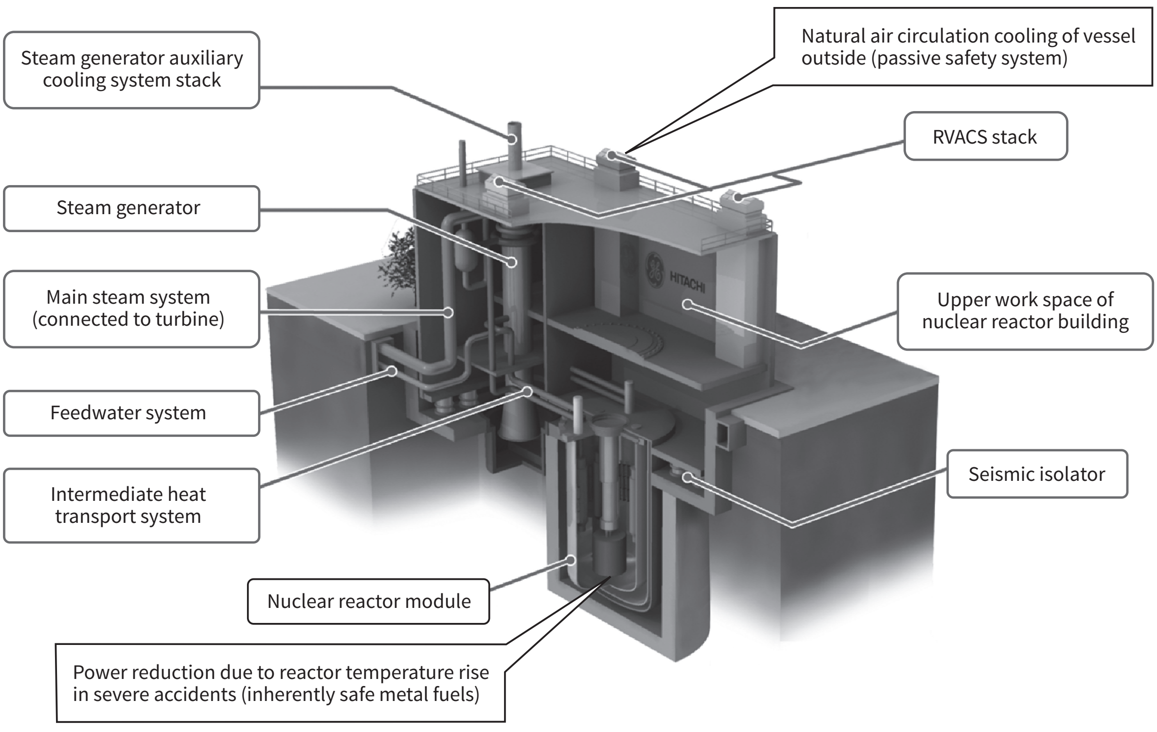
5. PRISM Innovative Small Modular Sodium-Cooled Fast Reactor

Japan is promoting a nuclear fuel cycle policy utilizing fast reactors to pursue goals such as reducing the amount and toxicity of high-level radioactive waste and maximizing the use of resources. The "Strategic Roadmap" for the development of fast reactors, revised in December 2022, calls for the concept to be finalized by around 2030 and for a demonstration reactor to be in operation by 2050. Hitachi-GE aims to introduce a PRISM-type fast reactor, which is economical, safe, and flexible, in Japan in the 2040s.

The PRISM design was initiated by the General Electric Company (GE) in the 1980s[6] and development continues today by GEH. **Figure 5** shows a conceptual diagram of the nuclear reactor module. The PRISM is a fast reactor that uses the reactor vessel auxiliary cooling system (RVACS) as a passive safety system facility to achieve long-term core cooling without power supply and operation during an accident, and metal fuel [uranium-plutonium-zirconium (U-Pu-Zr)] with inherent safety features, etc. And, it has a high density of heavy metals and average neutron energy, making it excellent in terms of economy and effective use of resources. In addition, a flexible plant configuration is possible due to the number of small modular reactors (311 MWe per unit) that can be installed to reduce the initial investment.

Figure 5 — Nuclear Reactor Module Concept (Provided by GEH)

The standard PRISM is comprised of two nuclear reactor modules and one turbine device in a single power block set. This diagram shows the standard nuclear reactor module.



RVACS: reactor vessel auxiliary cooling system

For the metal fuel cycle, a concept called the integral fast reactor (IFR) has been developed that integrates the metal fuel fast reactor, pyroprocessing, and fuel fabrication into an integrated facility. Pyroprocessing can simultaneously recover plutonium (Pu) and minor actinides (MA) and reuse them as fuel without removing them from the facility, providing high proliferation resistance and helping to reduce the amount and toxicity of high-level radioactive waste.

Furthermore, the Natrium*, being developed by TerraPower, LLC and GEH and selected for the Advanced Reactor Demonstration Program (ARDP), a program to construct a demonstration reactor in the USA in 2030, uses the PRISM concept for its reactor and a molten salt thermal storage system that stores extra heat according to the demand for electricity. This design option is intended to improve economic efficiency by responding to load variability and renewable energy output variability, and by generating power in response to the electricity market. The PRISM concept will also be demonstrated in this program, and Hitachi-GE, in cooperation with GEH, is considering an early introduce in Japan.

As a feasibility study for domestic introduction, Hitachi-GE will work with GEH and relevant institutions to study the conformity to the regulatory requirements assumed at the time of domestic introduction and introduction scenarios, as well as the safety of RVACS and metal fuel, and will develop a demonstration test plan including the fuel cycle. After the demonstration test, detailed design, and licensing, it aims to introduce a PRISM-type reactor in the 2040s.

6. Conclusions

This article has described Hitachi-GE's development of four new reactor designs HI-ABWR, BWRX-300, RBWR, and PRISM, with the goal of lowering the initial investment risk, securing a long-term stable power supply, and reducing radioactive waste toxicity.

Hitachi-GE will continue working to increase social receptiveness through actions such as reflecting nuclear power policies and incorporating user opinions, while using the clean energy of nuclear power to contribute to achieving carbon neutrality and quickly achieving the practical application of these four reactor designs.

* Natrium is a trademark of TerraPower, LLC.

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Development and Deployment of Reactor Decommissioning Technologies through Co-creation with Customers

In recent years, the decommissioning of nuclear power plants has been accelerating in Japan. Although it is necessary to shred the metal waste resulting from dismantling machinery onsite depending on the inspection and disposal method used after dismantling, from the perspectives of preventing fire and preventing contaminants from dissolving into steels, it is strongly preferred to apply a cutting method such saw blades that do not use fire. Based on this, Hitachi Plant Construction, Ltd. utilizes machinery it developed in-house to deploy fire-free equipment cutting solutions, and is contributing to safe operations and the proper disposal of waste, which are issues involved in the execution of decommissioning. This article describes Hitachi Plant Construction's track record in this area, introducing techniques such as shredding large equipment onsite with a bandsaw and removing contamination from steel surfaces by milling. It also provides an overview of technology under development based on future trends in decommissioning.

Takashi Kitahara
Tatsuya Iizuka
Ryo Moriguchi
Masaomi Wada, Ph.D., P.E.Jp

1. Introduction

Of the 57 commercial nuclear power plants that currently exist in Japan, 18 are undergoing decommissioning[(1), (2)]. Decommissioning refers to the dismantling and removal of equipment and buildings from a power plant that has ceased operations, while clearing away radioactive substances. Power companies that perform decommissioning work must safely execute a plan approved by the national government over a period of approximately 30 years, and depending on the state of contamination by radioactive substances, must properly dispose of wastes.

In general, decommissioning work starts with the dismantling and removal of (1) peripheral equipment from areas of the nuclear reactor with no contamination or comparatively little contamination (turbines, generators, steam condensers, etc.), continues with (2) equipment from areas of the nuclear reactor with comparatively greater levels of contamination (reactor pressure vessel, internal equipment from the vessel, etc.) and finally ends with (3) buildings and other such objects. Domestic reactors that are leading in the decommissioning process are currently in stage (1) in terms of the dismantling of peripheral equipment from areas of the nuclear reactor.

When it comes to the metal waste generated by this decommissioning, it is necessary to shred onsite to a size that is suitable based on the inspection and disposal methods established according to the level of contamination. While the use of fire, such as gas cutting, enables relatively efficient shredding to the desired size and shape, the risk of fire increases, and radioactive substances adhering to the surface of the material to be shredded cannot be removed if they are incorporated into the cut section, so fire-free cutting methods such as using saw blades, etc. are strongly desired.

It is against this background that Hitachi Plant Construction, Ltd. utilizes equipment such as a large, field-assembly-type bandsaw that it has developed in-house in deploying fire-free equipment cutting solutions, thereby contributing to the resolution of issues in decommissioning execution including operational safety and proper waste disposal. This article introduces Hitachi Plant Construction's track record in this area, and provides an overview of the technology under development based on future trends in decommissioning.

2. Track Record of Using Fire-Free Equipment Cutting Solutions

The large bandsaws that are one of the core types of technologies possessed by Hitachi Plant Construction can be used for fire-free cutting onsite without the need to transfer power generation turbines or other large objects to a dedicated facility. The company has a track record of more than 25 years of applying this technology for equipment removal and other projects at hydro-power, thermal power, and nuclear power plants, and has a lineup of models tailored for cutting objects of different sizes and shapes or installation locations, combined with a wealth of accumulated cutting data and know-how. Situations for utilizing these capabilities have increased in recent years, such as for decommissioning projects at nuclear power plants, and the company receives inquiries regarding solutions for a variety of different challenges from customers that need help with fire-free equipment cutting solutions. The next section will discuss bandsaws, followed by an introduction to one example of a new fire-free cutting technique that Hitachi Plant Construction came up with through co-creation with a customer.

2. 1 Onsite Shredding of Large Machinery Using Bandsaws

A bandsaw is an electric tool that rotates a loop-shaped saw blade in order to cut wood, metal, and other objects. There are a wide variety of different types of bandsaws depending on the application, from small versions that can be held in the hand to large stationary machines that are installed in factories.

Figure 1 shows a schematic diagram of the basic structure of Hitachi Plant Construction's bandsaws. The saw blade is attached to wheels arranged on the left and right side of the frame and held there with a constant level of tension. The wheel on the right side of the diagram is rotated with a motor to cause the saw blade to move over an orbital path. It is also possible to raise or lower the left and right wheels using a linear motion mechanism called a vertical jack. Lowering the orbiting saw blade with this type of machine configuration can vertically cut the object affixed between the wheels in two places at the same time.

Figure 2 shows a photograph and specifications for Hitachi Plant Construction's main lineup of bandsaws. The main attribute common to all models in the company's lineup is a structure that lets the frame and all parts of the mechanism be dismantled, assembled, and transported, so that it is possible to cut target equipment wherever it is installed. This makes the bandsaws particularly effective for dismantling and removing large equipment that cannot be transported as-is away from where it is installed due to mass and size restrictions. Also, in recent years machines have incorporated vibration sensors or laser displacement gauges to convert operating conditions to data, and efforts are being carried out to utilize this information to help make judgements regarding cuts without the need to rely on the five senses of skilled operators, or to automate cutting.

Figure 1 — Basic Structure of Hitachi Plant Construction's Bandsaw

The bandsaw vertically cuts the target object by causing a saw blade on the left and right wheels to move from top to bottom while orbiting.

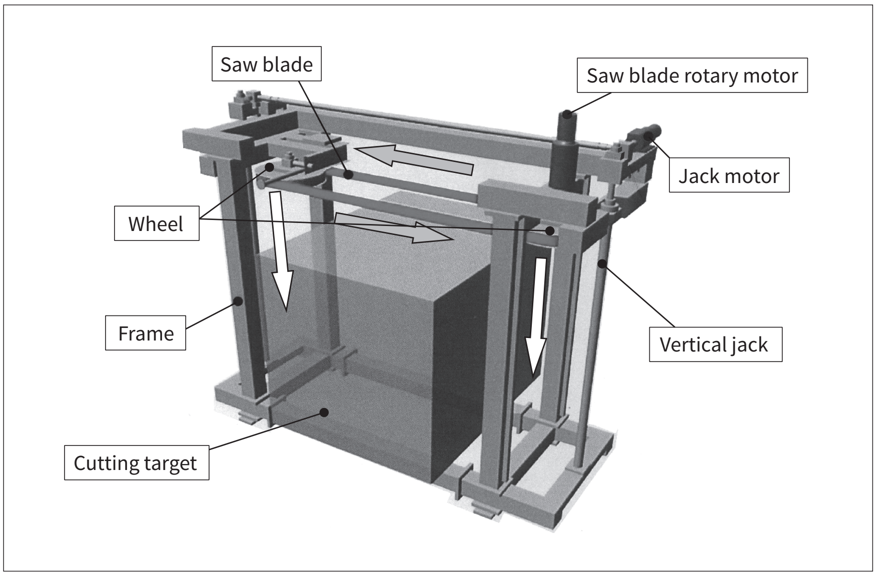
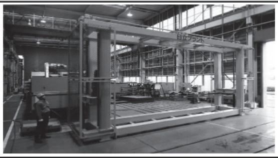
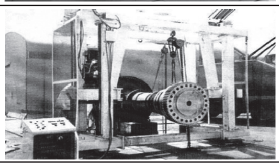
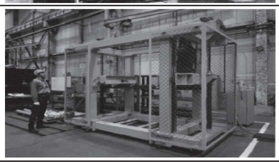
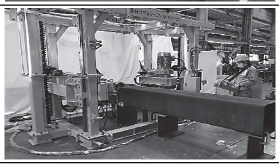


Figure 2 — Hitachi Plant Construction Bandsaw Lineup
The structure of the frame and various parts of the mechanism allows for dismantling, assembly, and transport. This main feature means that the bandsaw can be used to cut target machine onsite where it is installed.

Model	External appearance	Device external dimensions (mm) / Maximum cutting dimensions (mm)	Mass (kg)	Features
Extra-large		Width 10,000×height 6,000×depth 1,700	8,500	Can be assembled or dismantled onsite (common feature of all models) → cutting work can be performed onsite where target machinery is installed
		Width 8,000×height 4,000		
Large		Width 4,000×height 3,200×depth 1,700	4,500	
		Width 2,000×height 2,000		
Medium		Width 3,000×height 2,580×depth 1,700	4,300	Integrated transport on truck possible (no need to assemble onsite)
		Width 1,000×height 1,000		
Mobile		Width 3,750×height 2,640×depth 1,680	3,915	Assembly possible in narrow areas without the use of lifting equipment
		Width 1,000×height 1,000		

2. 2
Technique for Removing Contamination from Steel Surfaces by Milling

A nuclear power plant's exhaust stack is designed to release gaseous radioactive substances at a sufficiently safe level to ventilate the building and to generate during operation(3).

Hitachi Plant Construction received an inquiry from Chubu Electric Power Co., Inc. asking for a proposal of a new fire-free method to assist with the disposal of a dismantled steel exhaust stack, with a height of 100 m and a maximum diameter of 8 m, from a reactor at a plant currently undergoing decommissioning so that the stack itself could be widely utilized by society as nonradioactive industrial waste. The conditions for the work were as follows:
(1) Grind off the entire internal surface of the stack amounting to about 2,000 m^2, since trace amounts of radioactive substances flowed through the stack during operations.
(2) Generate scraps to prove that "the surface was definitely planed off," and recover these scraps.
(3) To eliminate the possibility of recontamination, do not allow the grinded surface to come into contact with tools or scraps.

Company engineers who had participated in the development or operation of fire-free cutting equipment considered these conditions and proposed equipment and techniques using the "face milling tool," which is one type of rotary cutting tool.

Figure 3 — Cutting of Board Surface with Face Milling Tool
Suitable for efficiently scraping wide surfaces, and always produces scraps from scraped areas. Also, moving the tool from top to bottom causes the scraps to fall due to their own weight.

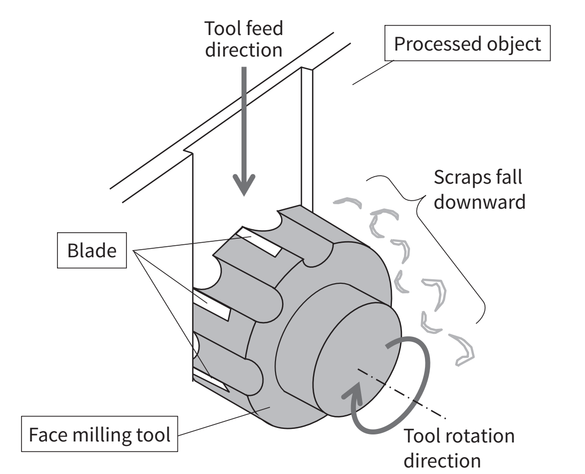


Figure 3 shows this face milling tool along with an image of the steel surface being cut. The face milling tool has multiple blades arranged around its circumference, and proceeds by shaving off a flat plane that is the diameter of the tool while sending the milling cutter or target object in a direction at a right angle to the axis of rotation. This tool is suited for efficiently scraping at a wide flat plane, and always generates scraps from the scraped locations, while preventing scraps from adhering to the processed surface as they fall due to their own weight as the tool is moved from top to bottom as shown in the diagram. Since the features described above

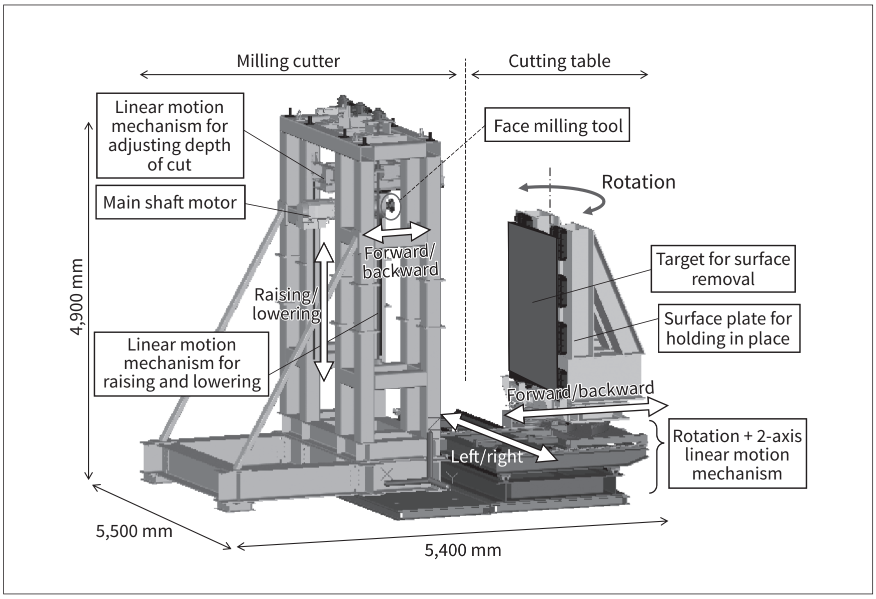


Figure 4 — Equipment for Removing Contamination from Steel Surfaces

This equipment is comprised of a milling cutter and a cutting table. The milling cutter includes a 15-kW motor that rotates the tool around the main shaft, and an electronic linear motion mechanism that raises and lowers the main shaft, and an electronic linear motion mechanism that adjusts the depth of cutting in the direction of the thick steel plate. The cutting table side includes a surface plate for holding the shredded piece of the exhaust stack in the vertical direction, two shafts with electronic linear motion mechanisms for moving the surface plate forward/backward and left/right with respect to the milling cutter, and a rotating mechanism that moves the curved exhaust stack shredded piece around a vertical shaft to face towards the milling cutter.

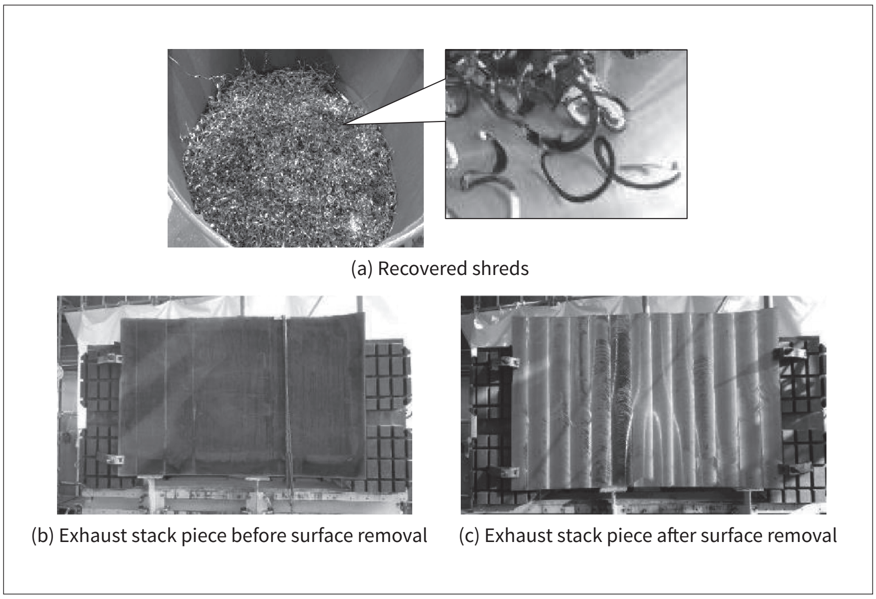


Figure 5 — Removal of Steel Surface with the Equipment

As shown in (a), the characteristically arc-shaped shreds created by cutting the metal are produced, and it is confirmed that they are reliably "removed" from the steel surface.

comply with the technique's requirements, Hitachi Plant Construction developed "equipment for removing contamination from steel surfaces" using this face milling tool.

The structure of this contamination removal equipment is shown as a schematic diagram in **Figure 4**. The device is comprised of a milling cutter part and a cutting table. The milling cutter is comprised of a main shaft that rotates the tool with a 15-kW motor, an electric linear motion mechanism for raising and lowering the main shaft, and an electric linear motion mechanism that adjusts the depth of cuts in the direction of the thick steel plate. The main shaft's rotational frequency is 300 min^{-1}, the diameter of the attached tool is 125 mm, and this tool can be swapped out with another tool of a different diameter if necessary. The speed at which the main shaft rises and falls was set to a maximum of 500 mm/minute to meet the customer's requirements for a processing speed of 300 mm/minute for the entire process. To ensure that scraps would definitely be formed from the cuts to the surface, it was decided to set the depth of cutting in the direction of the plate thickness to around 1 mm.

Based on a consideration of ease of use during transport within a site and other such issues, the cutting table side was configured with a surface plate that fixes the shredded pieces of the exhaust stack in a vertical orientation after they are segmented in advance with a height of around 1 m and a width of around 1.5 m. This surface plate has electronic linear motion mechanisms that can move in two axes with respect to the milling cutter, namely, forward/backward and left/right. Furthermore, it has a turning mechanism around the vertical axis to position the shredded pieces from the curved exhaust stack to face towards the milling cutter.

Figure 5 shows the results of the process for using this device to remove the steel surface. **Figure 5** (a) is a

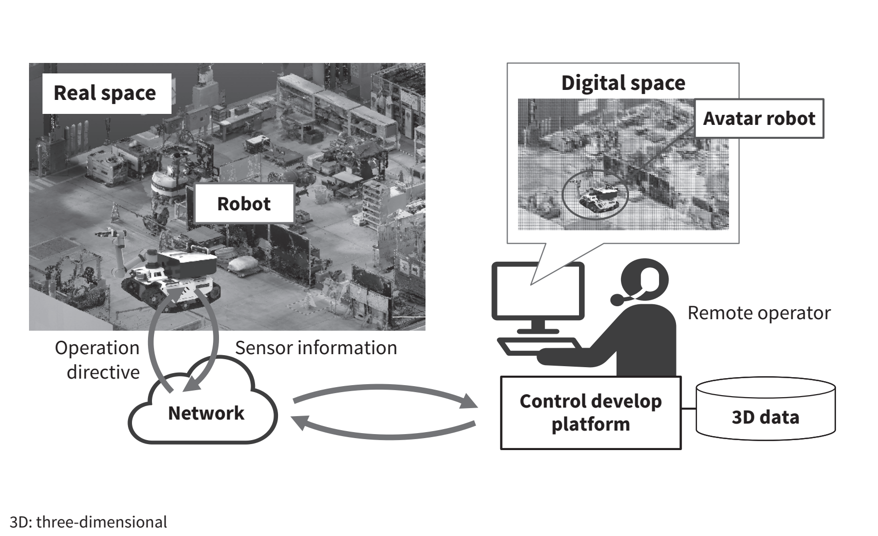


Figure 6 — Overview of Remote Robot Operation System under Development

The operator pilots an avatar robot that moves in exactly the same way as the actual robot based on various types of sensor information in a faithful reproduction of the site in a digital space. Since the blind spots of conventional cameras are eliminated, complex operations can be performed easily, safely, and reliably while visually confirming operation from any viewpoint.

photograph of recovered shreds. Shreds were obtained in a characteristic arc shape after the metal was cut, making it possible to confirm that the steel surface was definitely removed. Also, as described previously the processing direction was always facing downward, and a cover was attached to prevent the scattering of shreds around the equipment, with compressed air blown over the tool to prevent the adherence of shreds. **Figure 5** (b) and (c) show pieces of the actual exhaust stack before and after the removal process. The customer's requested work schedule was met, and up to a maximum of 500 mm/minute of the surface of the exhaust stack was cut while using φ100, 125, and 160 mm tools depending on the radius of curvature and the state of the surface.

3. Developing Technology for Dismantling Nuclear Reactor Equipment

The previous section introduced one example of a fire-free equipment cutting solution for decommissioning of a nuclear power plant by shredding a large structure using Hitachi Plant Construction's conventional bandsaw technology, as well as a new technique, developed through co-creation with a customer, for removing the contamination from a metal surface using a milling cutter. The company works to satisfy customer needs for onsite decommissioning in this way while at the same time conducting research and development to anticipate the new needs of the future. One key concept is "transitioning to remote operation."

Plants leading the way with their decommissioning work are planning to start dismantling operations in the nuclear reactor area soon. The need for fire-free cutting will likely remain high, and it will be necessary to take countermeasures to reduce the exposure of workers during this dismantling work due to the comparatively high level of contamination. Therefore, the company is developing a waterproof bandsaw for use underwater to take advantage of the ability of water to shield from radiation.

In this environment, it is also desirable, as much as possible, to do this equipment shredding and other dismantling work remotely. Hitachi Plant Construction is currently collaborating with a customer, which is seeking to decommission next-generation reactor, to develop a robot system for decommissioning that applies digital twin technology. Although the conventional method of remotely operating this type of robot involved viewing images from a camera installed on the equipment itself or onsite, it was difficult for the operator to accurately and intuitively judge whether or not the robot was operating correctly just from a flat camera image.

Figure 6 illustrates the concept of Hitachi Plant Construction's robot system. With this system, instead of the operator controlling a robot viewed with a camera, the operator pilots an avatar robot that performs the exact same motions as the actual robot, based on various types of built-in sensor information, by faithfully reproducing the site using laser scanner measuring instruments and three-dimensional computer aided design (3D-CAD). This eliminates the blind spots of conventional camera systems, making it possible to easily, safely, and reliably perform complex operations such as moving through a narrow and complicated set of passages, avoid obstacles in front of it, and grabbing objects at the end of the passages with a manipulator while viewing them from a free viewpoint.

4. Conclusions

Hitachi Plant Construction has accumulated more than 25 years of experience and knowledge regarding the cutting of various objects onsite with bandsaws and other machinery it has developed in-house. In the future, the company will combine new forms of information (digital) technology (IT) with operational technology (OT) to collaborate with customers on the creation of new IT and OT solutions, while contributing to the realization of a carbon-neutral society with the proper disposal of waste using fire-free cutting methods.

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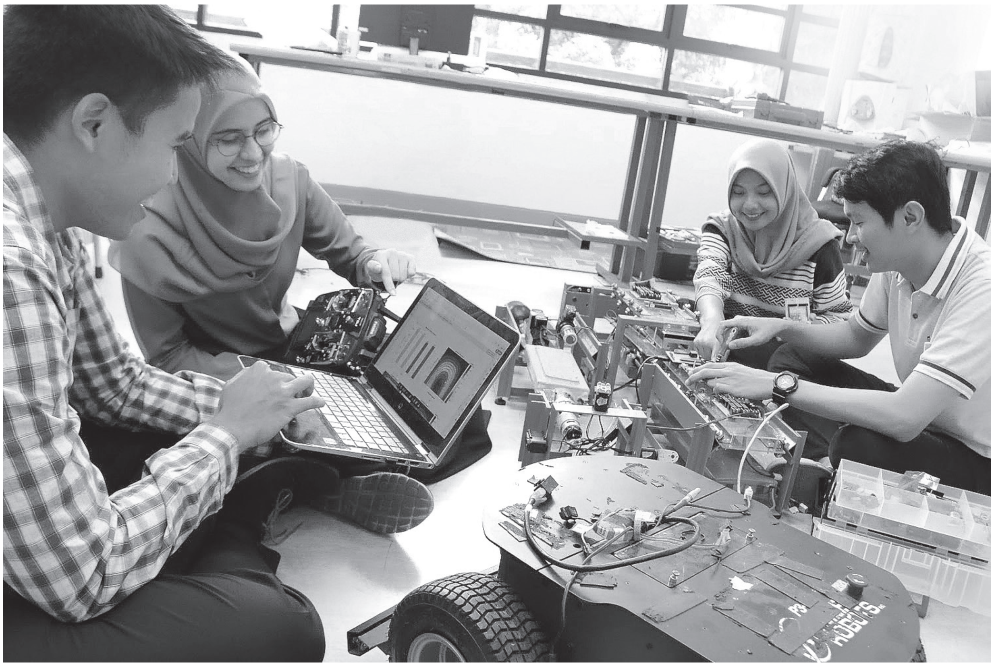
Academia-Industry Partnership: A Cornerstone of the Future Energy System

In this Perspectives, Akilur Rahman, Chief Technology Officer at Hitachi Energy India Limited, argues that in order to nurture future technology pioneers and net-zero entrepreneurs, industry and academia need to deepen their partnerships and invest in diversity to spark out-of-the-box thinking required to speed up the energy transition.



Akilur Rahman
CTO, Hitachi Energy India Limited

New Talent Profiles for the Energy Transition

Traditionally, educational institutions passed on knowledge to their students who then applied it in industry. But we now know that building expertise is bi-directional: From academia to industry and industry to academia. In today's fast-paced world, time is of the essence, and this imperative is no different in education. A concurrent approach to teaching science in conjunction with hands-on industry experience is the ideal way to nurture new talent.

Government targets for reaching climate neutrality range from 2030 to 2070. This long-term view requires the industry-academia partnership in the energy transition to implement a more holistic approach with dynamic engagement and eyes on the broader picture in place of siloed thinking.

From left to right: Professor Iwa Garniwa; Professor Reini Wirahadikusumah; Niels de Boer; and Professor N Subrahmanyam.

The road to a net-zero economy demands a change in talent profiles, a meshing of expertise from various fields covering not only engineering, computer science, chemistry and physics, but also sociology and economics. Today's generation of budding talent has great potential to become knowledge multipliers, a workforce which is not trapped within its area of expertise but which thrives on collaboration and co-creation. The energy transition needs not only top-notch technologies, products, and services but also a huge amount of this new talent which we in the industry have an obligation to attract in order to pave the road to a low-carbon future.

How are academic institutions adapting to offering concurrent teaching methods that suit the needs of the energy transition? How are academia and industry facilitating the much-needed hands-on experience and how are they promoting adequate thought and gender diversity in key scientific degrees and job functions?

I had the pleasure of obtaining insights into these questions from some of South Asia's finest engineering academics:

- Professor Iwa Garniwa, Rector at the Institute of Technology PLN in Indonesia;
- Professor Reini Wirahadikusumah, the first female Rector of the Institut Teknologi Bandung (ITB);
- Niels de Boer, Program Director at the Centre of Excellence for Testing & Research of Autonomous Vehicles at the Nanyang Technological University (NTU) in Singapore; and
- Professor N Subrahmanyam, Head of the Department of Electrical Engineering at the National Institute of Technology, Warangal (NITW) in India.

Role of Academia in the Energy Transition

Academic institutions have a fundamental role in delivering the message about the urgency of combating climate change and speeding up the energy transition. Having already provided the foundation of what we know about tackling climate change, our universities contribute to advancing a more sustainable world by developing a new understanding of and insights into current energy system problems. They are a key stakeholder in the societal commitment to combating climate change and a source of knowledge independent from governments. They are also a resource pool for new talent capable of exploring the next technological breakthroughs in energy. It's critical that today's students help achieve our 2030, 2050 and 2070 carbon reduction goals and that they share in the culture and behavior of wanting to create a cleaner future.

NTU's Niels de Boer said nothing is more convincing to an engineer than seeing the direct, positive impact their own project results can have. Be it the amount of carbon emissions saved by a lithium-ion battery system in an electric vehicle or the number of clean electrons a solar photovoltaic installation can produce to power a home.

As a master in electrical power system engineering myself, I see making the connection between theory and practice as the most important means to give students the skills, confidence, and motivation to work in the energy transition.

As an industry, we must help establish the necessary laboratories and research centers where students can master and apply the latest technologies to learn, research and innovate. Universities are indeed uniquely positioned to become important test beds for emerging technologies, processes, and strategies because they combine different research disciplines and consequently provide an unbiased environment for exploring new ideas. With digitalization driving more and more convergence between different technologies, the energy industry needs strong partnerships with academic institutions in order to give the engineers of the future an inter-disciplinary education and skills and to optimally prepare them for working in the energy transition.

Some institutions are already reaping the benefits of strong industry partnerships. Students at India's NITW, which offers a Smart Electric Grid master's program inspired by feedback from industry partners, have strong employment prospects. "We are seeing this happening in terms of our students getting ready for the industry and getting good job placements," said Professor N Subrahmanyam.

Offering Practical Experience

South Asia has recently seen a wave of innovative and high-tech power system solutions. For example, the Australia-Asia PowerLink project, which plans to lay a 4,200-kilometer long HVDC submarine cable—the world's largest—between Australia's Darwin and Singapore, transmitting Australian solar power to the metropole. In the Indian Himalayas, one of the world's biggest solar plants is being developed, targeted to have a capacity of 9 GW and to be combined with a 12 GWh battery-storage system and a 4 GW wind farm.

Impressive examples like these inspire students to help push the boundaries of electrical engineering, an ambition that is indispensable for enhancing the energy transition. Students' aims need to be encouraged in conjunction with where the industry requires innovative thinking and where they can make real impact on fighting climate change. Universities are a breeding ground for ideas that can leapfrog existing thinking and where out-of-the-box experimenting and research can test radically new approaches.

Many academic institutions have already laid the foundations for partnerships with industry. For example, Australia has seen a number of successful joint research projects between universities and the industry on renewable energy, resulting in total research investments from government and the public and private sectors of more than AUD54 million. The funding went to green energy projects including the production of biogas from sugarcane and investigating how robots could capture data for solar installation diagnostics.

Further, the Indian Institute of Technology Madras (IITM), for example, is running a highly respected start-up hub for entrepreneurs incubated through the university. The initiative has supported a number of innovative energy technology companies that are able to apply cutting-edge university research in an industrial setting. Ideas are converted to applications in the areas of EV, renewables, energy efficient equipment, solar-DC, energy management, quantum safe encryption, green building cooling, energy storage, etc. led by students, alumni and faculties together with industries.

At the Jakarta-based Institute of Technology PLN (IT PLN), an engineering-focused university directly supported by Indonesia's national utility PLN, students who graduate are also awarded a certificate of competence based on practical experience they gained during an industry internship as part of their degree. IT PLN's Professor Iwa Garniwa told me this close collaboration aimed to enable students to gain valuable employment in the industry.

Partnerships between industry and academia must also act as a catalyst for modernizing teaching curriculums. As future employers of those gaining engineering degrees, energy companies can help keep course content current and relevant and they can suggest topics for research projects. For example, the Smart Electric Grid master's program of NITW was developed through a comprehensive input from the industry, adapting the curriculum to meet emerging knowledge and skills requirements and driving new research activities on smart grid technologies and digital transformation. Often, these types of collaborations are anchored in the students gaining practical experience in the form of internships and work placements at the partnership companies. These allow future engineers invaluable access to potential employers but also to unique sets of data for new energy research and technologies.

Creating 'Living' Laboratories

Teaching about the energy transition mustn't stop at the curriculum. Many universities are improving the sustainability credentials of their own campus buildings and infrastructure. But much more can be done to offer students and staff live laboratories which in parallel reduce the universities' own carbon footprint. These are excellent opportunities for academia and industry to deepen partnerships of mutual benefit.

In India, which the International Energy Agency estimates could create a low-carbon technology market worth

Students at ITB

$80 billion by 2030, universities are investing heavily in creating low-carbon campuses. IITM, for example, is home to a state-of-the-art electric bus infrastructure project which pilots Hitachi Energy's flash charging technology and Indian bus manufacturer Ashok Leyland's electric bus designs. Students and staff alike will be using these electric buses to move around campuses, experiencing firsthand the benefits of low-carbon mobility and creating an actual transfer of knowledge regarding new technologies for the energy transition. Another similar example is NITW's Smart Electric Grid Laboratory, which Hitachi Energy helped set up and aimed to become a space to incubate new research ideas on integrating distributed renewable energy resources into Smart Electric Grid, among others.

"In order to approach net zero, we need to think about how to cut carbon footprint first from our backyard," is how ITB Professor Reini Wirahadikusumah made her point. The Indonesian university recently established a green campus where a forest and botanical garden surrounding the site act as practical laboratories, for example for how to use bio-based materials for renewable energy conversion.

Attracting New Talent

Focusing on academia being a place of out-of-the-box thinking and offering industry-linked research opportunities will also help make engineering and other energy transition related studies more interesting to entry-level students. Attracting talented graduates to work on the energy transition remains one of the sticking points as competition from other sectors is fierce. We urgently need young people who can confidently go beyond conventional thinking and who can try new ideas in the best possible setting.

Among other approaches, educators must help students understand the significant opportunities and career progression in the field of energy, such as electric power systems and energy engineering, which have been early developers and adaptors of software, automation and digital technologies in the industry. Be it domain technologies such as energy storage, green Hydrogen, distributed energy resource management, power electronics, HVDC or digital technologies including big data, cloud computing, AI-ML, AR-VR, digital twin, block chain, cyber security, opportunities are plenty. What is important is they are for real and helping to achieve energy transition targets, probably the domain with maximum convergence of these technologies.

Not just the technologies, but their positive impact on the society is tremendous. Prof. Subramanyam of NITW said that "economic prosperity and growth of society are directly related to electric energy developments in the energy sector." The importance of developing our energy system must be impressed upon future students early on to ensure they are motivated to take on the challenges confronting the electric power industry.

Life-long Learning

Attracting talent to the energy transition does not end at graduate level. An increasingly important factor in weighing a career move is whether an employer offers opportunities

for life-long learning and gaining additional qualifications. Companies must focus on retaining top talent by providing top-notch further education and career development. These training programs need to be put in place to help existing employees map out clear and purpose-driven career paths and to bring them up to speed on operating the latest innovative technologies and products.

The complexity of energy technologies is deepening at lightning speed, which means that both those employed directly in the industry and those teaching the next generation of workers need to stay up to date. Employers need to allow time for staff to attend relevant training courses and enroll in higher education courses needed to advance critical skills and sustain competence. Professional development should focus on new teaching practices adaptable to the digital mindset of young people as well as introduction to existing digital solutions being used in the industry. These retraining efforts can also tap industry professionals who can provide the practical industrial experience that some academic institutions need. NTU in Singapore, for example, is already preparing to increase its course offerings for professionals, said Niels de Boer. "Keeping existing staff's skills current is going to be an important role for universities in the future because the technology is changing faster and faster, and it's getting more challenging for engineers to stay up to date.

Diversity at the Heart of the Transition

By nature, energy is a highly intertwined ecosystem that dynamically controls and protects our world and which touches all aspects of life. It has tremendous potential to connect humans, machines and intelligence in working together for a sustainable future. We therefore need to incorporate diversity of thought, geography, culture, gender and generation into our academic research as well as our professional environment. Academia and industry must integrate a 360-degree view on diversity to foster collaboration and inclusiveness for the benefit of scientific progress.

Encouragingly, energy transition research and education is already a globally-minded discipline that includes several generations of workers. But one important aspect continues to lag: Gender diversity. Women represent only around one third of the workforce in renewable energy, according to the International Renewable Energy Association. Although this percentage is higher than in the overall energy industry, the energy transition can only be effective if more women are included in shaping where the change is taking place.

The number of women graduating with engineering degrees is rising but remains notoriously low. Universities, colleges, and high schools have undertaken initiatives to encourage more female students to take up science degrees, and many energy companies have programs in place to recruit and promote female staff. However, a deeper collaboration on the topic between academia and the industry must bring further improvement. Energy companies should, for example, present female engineering role models more prominently and offer mentorships to link young female engineers with women in leadership functions.

Although more and more companies and educational institutions are launching initiatives to attract and retain female students and staff, more needs to be done. Changes can start with motivating and supporting female students to choose and pursue engineering courses. In India, for example, female students from rural backgrounds are supported by Hitachi Energy and other organizations as part of the "Women in Engineering" program for undergraduate courses. It provides them with educational aid, materials, coaching, mentoring, and summer schools in higher education institutions to help them advance their careers or prepare them for gaining employment in the industry.

In Australia, the Women in Climate and Energy Fellowship (WICEF) supported by the University of Technology Sydney offers female entrepreneurs access to workshops and mentoring to help them launch clean energy and climate tech start-ups.

Attracting more females to the energy transition will only work if we encourage as many young women and girls as possible to choose scientific degrees and subjects at universities and schools. In many places, this requires a deep-rooted societal mindset change that needs to be overcome.

Hiring more female senior members of staff will also go a long way at the universities themselves. ITB recently appointed four female heads of research centers, including Dr. Ir. Retno Gumilang Dewi, M.Env., Eng.Sc—Head of Center for Research on Energy Policy. This is a step in the right direction that many more institutions need to follow.

Conclusion

The academia-industry nexus is a crucial cornerstone of the future of the energy transition. Educational institutions are the testing grounds for new ideas that make away with old thinking and really push the envelope on energy technology innovation. We need to leapfrog conventional technical, economic and social thinking to create fresh solutions for a low-carbon world. Academia plays the important role of nurturing fresh talent that is required to bring the energy transition to the next level and industry has to help by providing fertile grounds for experimenting through deep-rooted partnerships.

The energy industry is intrinsically linked to education as it has an obligation to offer employees life-long learning opportunities that will help broaden the collaborative approach needed to tackle the energy transition challenges. The red thread winding its way through the energy transition is investing in diversity. Academia and industry need to help foster a change in the societal mindset that allows a 360-degree view on diversity, may it be related to gender, thought or age. It's only if we collaborate and include a multitude of viewpoints that the energy transition will truly flourish.

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Energy System to Achieve Decarbonization

Energy Systems for Achieving Carbon Neutrality

Keisaku Shibatani

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