Efforts to Develop Environmental Prediction Technologies for Carbon Neutrality

— Recycling carbon dioxide and IoT data —

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Introduction

Looking ahead to 2050, by which carbon neutrality is expected to be achieved, we are now in a transitional period. As we progress toward that goal, new visions about energy sources and how mobility should be as energy consumers are materializing. For example, renewable energy is an important factor in decarbonizing, but solar power and other kinds of renewable energy that are unstable in supply require adjusting functions or storage batteries that do not use carbon-based fuels. At the same time, whether electricity is suitable to store surplus renewable energy must be examined from the perspectives of cost and storage capacity.

The electrification of automobiles, which consume energy, is also in a transitional period, with internal combustion engines and hybrid vehicles still in widespread use. In this context, to efficiently and maximally utilize various renewable energy sources, we need technologies for producing and storing not only electricity but also hydrogen, ammonia, and e-fuels (synthetic fuels) like methane synthesized using captured carbon. In addition, the transport sector, as a major energy consumer, must address both the need to secure power sources and reduce carbon dioxide emissions.

At the Soma IHI Green Energy Center (SIGC), IHI has been studying and conducting demonstration tests on energy carriers like hydrogen, ammonia and e-fuels and how they can be used for surplus electricity from solar power generation. For example, the Odekake Minibus, a mobility service that employs methane synthesized using renewable energy, has the potential to become an important transportation method for the local people. In addition, the use of oxygen produced through the water-electrolysis of hydrogen in aquaponics could serve as a stepping stone in the advancement of primary industries.

To apply such renewable energy to mobility, farming, and other regional activities, we must carefully balance and match energy demand with supply. With a surplus or shortage of either of these, such applications do not work. This approach is similar to building a distributed power system that functions as a stand-alone, off-grid system, utilizing renewable energy sources with unstable supply. It is an effective attempt not only to realize carbon neutrality but also to improve energy resilience and prepare for disasters. What is important here is optimally matching constantly changing renewable energy supply and demand, and this matching requires accurate predictions of both renewable energy generation and the corresponding demand.

Applying mathematics to environmental prediction technologies

To match the fluctuating supply of renewable energy with its varying demand, while considering storage costs and conversion efficiency, it is necessary to optimize the portfolio of electricity generated from renewables, and energy carriers like hydrogen and methane. Applying mathematics is an effective approach for achieving this. Specifically, the balance between ever-changing supply and demand of renewable energy can be described using a mathematical model known as a dynamical system. This enables us to make predictions, optimally match supply and demand in real time, or theoretically improve the robustness of electricity, mobility, and communications as multiple networks. Knowing the theoretical background of a target scene also enables us to make factor analyses and is helpful for making predictions and designing efficient systems. In fact, artificial intelligence technologies and other mathematical methods have already been applied to predict renewable energy generation.

We have proposed a methodology that works with limited computational resources and small data, which are practical issues in conventional prediction methods using artificial intelligence, and demonstrated its effectiveness based on examples of predicting traffic congestion. Furthermore, we are also developing a video-based anemometer technology that applies the same principle to estimate wind directions and speeds. The underlying idea behind this methodology is that by fully utilizing data (information) that is often overlooked, we can uncover new value in the information we use. This is similar to carrying out the SIGC's MOTTAINAI practice, which is founded on the concept of local consumption of locally generated renewable energy in an intangible manner. Methane synthesized using renewable energy is based on the idea of carbon recycling which is the process of reusing carbon dioxide emitted to the atmosphere, and our prediction method can be considered a kind of data recycling in that data obtained constantly from detectors and other infrastructures is reused. We also aim to accelerate the shift to carbon neutrality by recycling tangible and intangible resources simultaneously to improve the efficiency of renewable energy use.

One scenario goes like this. While constantly obtained meteorological measurement data is reused to predict renewable energy generation, carbon is recycled to synthesize methane and surplus energy is used without any waste. As a result, carbon neutrality is accelerated. Naturally, there remain technical hurdles associated with data selection and carbon capture, but the application of mathematics is effective in that such scenarios can be examined on the assumption that they are achievable in practice.

Recycling data

The prediction methodology we have proposed is explained here briefly. Big data obtained from IoT sensors, including the Internet, is essential to recent advances in artificial intelligence technology. ChatGPT and other kinds of generative AI require huge amounts of data for learning and computational resources. On the other hand, when it comes to unprecedented disasters such as torrential rains and emerging infectious diseases or unobserved places such as polar regions, it is difficult to collect sufficient data for standard deep learning. It is also challenging to simulate a phenomenon that changes with time, such as traffic congestion due to unexpected traffic accidents, in real time owing to the lack of computational resources. The artificial intelligence technologies mentioned above derived from the conventional AI methodology of making quality predictions by building an appropriate model based on the past data and conducting simulations with digital computers. Consequently, it is practically significant to examine how to perform desired computations when you cannot obtain sufficient data or an appropriate model. Then, we proposed and have been examining a new methodology for learning technology that can also be used in cases where standard artificial intelligence technologies based on big data cannot be applied. With a special focus on data recycling, we have been trying to predict the occurrence of traffic congestion using data from existing detectors along expressways, and examining high-speed learning and how to secure prediction accuracy based on small data as an artificial intelligence technology that helps to achieve carbon neutrality as mentioned above.

Selecting and focusing on learning data

In this section, I explain the concept of reservoir computing, which has been attracting attention as an alternative technology to deep learning, and the concept of environmental prediction computation, which is an application of reservoir computing.

Reservoir computing featured as an interesting computer architecture in the Report on Research and Development (2023), published by the Japan Science and Technology Agency's (JST) Center for Research and Development Strategy. Since what physically exists can be used as computational media, its potential as an analog device is also being discussed.

We proposed a framework called computation harvesting as a form of this computation method that uses actual phenomena, and have been examining examples of its demonstration. In this framework, patterns of physical change in an actual phenomenon are extracted. The extracted change patterns, which we consider as a kind of process, are used as computational resources. For example, on an expressway, vehicle flow data (average speeds and traffic volumes, etc.) is constantly extracted by vehicle detectors as change patterns. By combining groups of patterns extracted by detectors in different locations, we can make short-term predictions of traffic congestion with high accuracy. In verifying real data for a certain route, our method achieved rapid learning that is about 2 000 times faster than deep learning with comparable accuracy. In addition, the verification results showed that by appropriately selecting certain data (focusing on data just before and after the occurrence of traffic congestion), which would lower the accuracy of prediction for deep learning due to a lack of sufficient learning data, our method could make predictions based on small data with higher accuracy than deep learning based on big data. Furthermore, the characteristics of the algorithm enable us to verify the explainability of prediction results and examine methods to avoid traffic congestion. An important characteristic found in this example is that desired computation can be realized by reusing some of the data constantly collected by conventional IoT sensors. In other words, data is recycled.

The application of mathematics is especially effective in that the single prediction methodology can be applied to different scenes, so we applied exactly the same methodology to another situation. Specifically, we predicted the onset of sepsis by recycling examination results from intensive-care units, and as a result, our methodology proved to be effective. If healthcare IoT data can be collected from homes, the risk of emergency transportation can be estimated based on that data, and this estimate can be combined with the prediction of current traffic conditions to provide a smart emergency mobility service. **Figure 1** shows the prediction methodology based on data recycling. Currently, we are trying to summarize the mathematical background that shows the proposed method can make suitable predictions, and clarify what properties are possessed by scenes where this prediction method works effectively. In particular, we are focusing on applying this method to scenes in the environmental field.

An advantage of clarifying the theoretical background that makes this computing technology workable for environment-related predictions is that energy can be saved by lowering computation costs and fast computations can be made at the edges. Another noteworthy point is that since this method assumes that information from sensors that is usually unused is used, it does not require infrastructure costs. As an application to renewable energy, we are considering applying this technology to meteorological forecasts to develop a low-cost, fast, and large-scale prediction system in the energy field.

Application to carbon-neutral mobility systems

We are examining the idea of applying this technology to both smart energy and smart mobility. Specifically, this involves applying the concept of data recycling mentioned above to realize autonomous prediction and avoidance of traffic congestion, and combining this with renewable energy to optimally match demand and supply in both electricity and mobility at the same time.

In Council for Science, Technology and Innovation (CSTI), Cross-ministerial Strategic Innovation Promotion Program (SIP), the third period of SIP "Smart energy management system," we have been working on research and development with the aim of realizing social implementation of self-sufficient renewable energy and linking it with electric vehicles, methane gas vehicles, and other kinds of next-generation mobility, under the theme of a "Carbon-neutral Mobility System." At the new campus of Tohoku University set as a target site, we are aiming to convert solar power and various other kinds of renewable energy into electricity, hydrogen, methane, and other forms of energy sources, store them, and provide an optimal form of mobility that meets the needs of students and faculty members at the university. **Figure 2** shows a grand design proposal for the Tohoku University Green Campus. Mathematical models and the above-mentioned prediction technology based on data recycling are also applied to implement this energy management system. Moreover, we are also aiming to develop an energy carrier dynamic optimization theory that helps to save energy and achieve carbon neutrality. Especially in regard to carbon recycling, IHI's standard methanation system plays an important role in synthesizing methane from

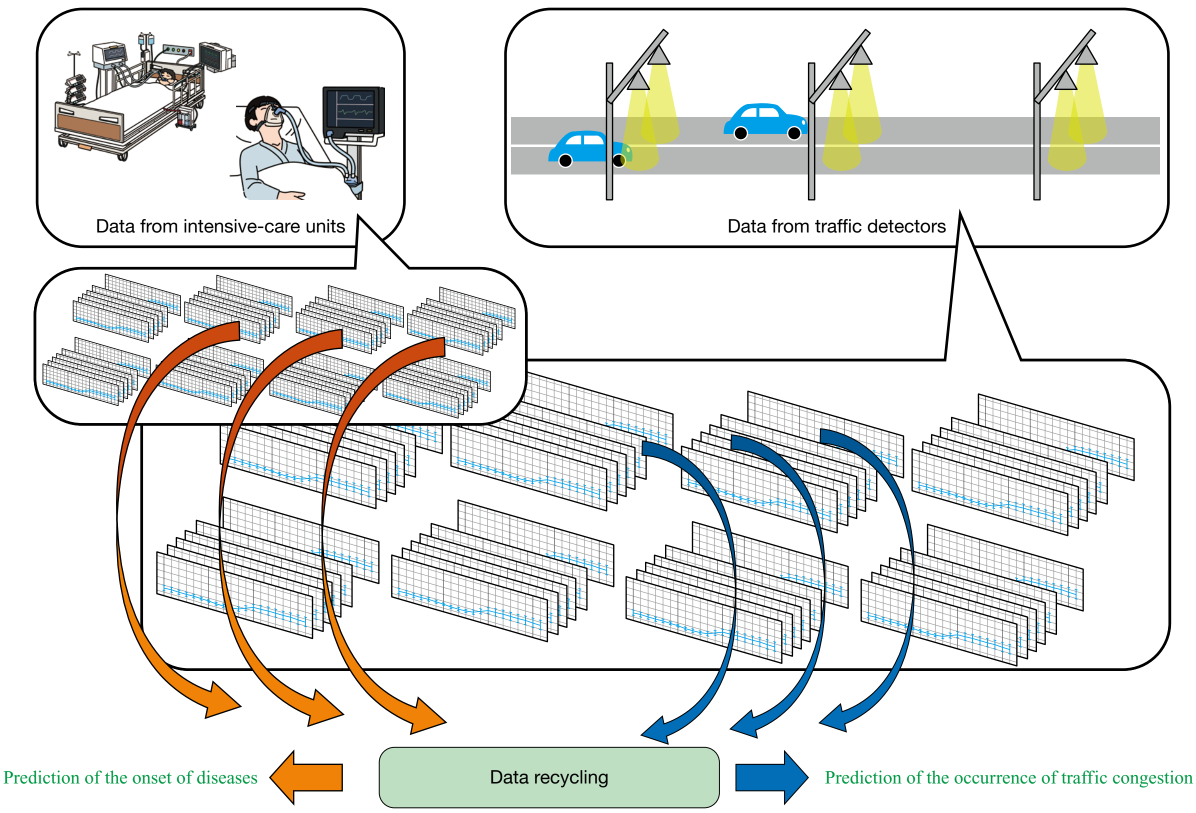
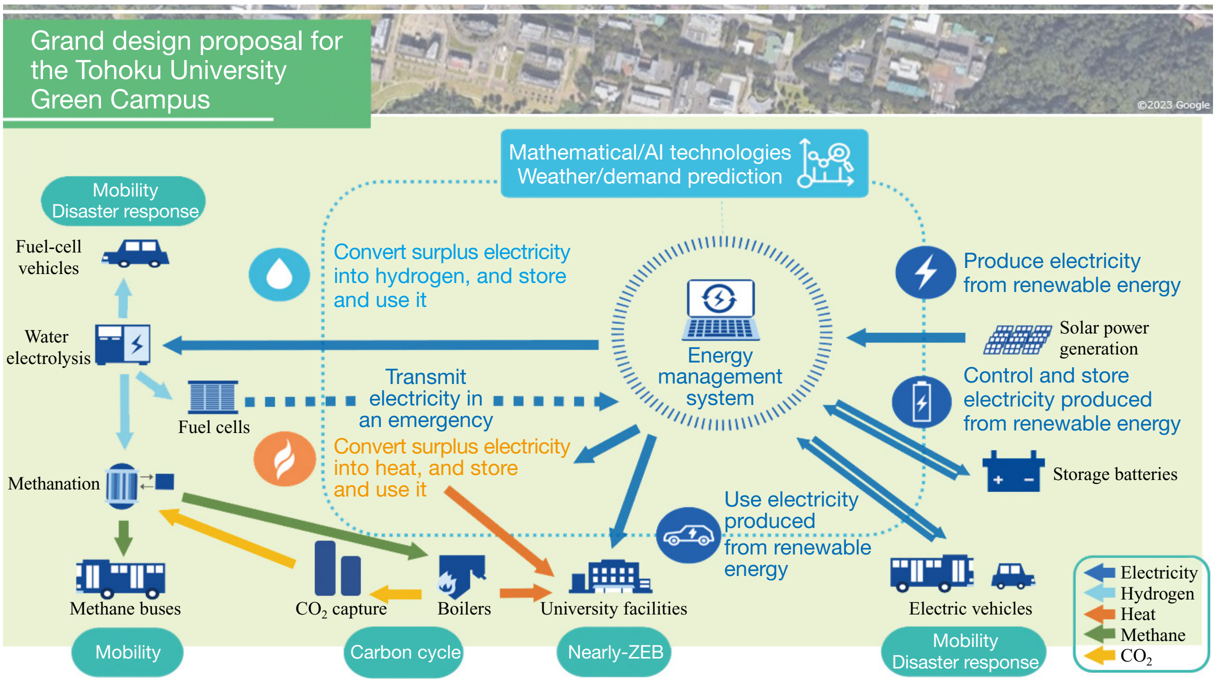


Fig. 1 Prediction methodology based on data recycling



(Note) Nearly-ZEB combines energy saving and energy creation to reduce energy required.

Fig. 2 Grand design of the Tohoku University Green Campus

carbon dioxide and green hydrogen. To predict demand for electricity and mobility, an energy management system that recycles and effectively uses IoT data on electricity consumptions in the university buildings and on the movement of people, such as the usage of the university's loop buses, will be built. This project is being carried out by four universities, led by Tohoku University, one national research and development agency, and three companies, including IHI, with the aim of completing the Tohoku University Green Campus plan as shown in **Fig. 2** at the end of the five-year project.

This article introduced the framework for an energy management system that is based on IHI's efforts to use green energy and is aimed at realizing carbon neutrality through application to mobility, where various kinds of power are used. It explained a methodology for environmental prediction technologies where data recycling works effectively in both tangible and intangible forms, with a particular focus on the application of mathematics. In the future, we will promote research and development that leverages the unique strengths of a certain university, with a focus on multiple objectives. This will involve using mathematical approaches to connect diverse data from various fields, such as energy, transportation, healthcare, and education.