Hydrogen Utilization in Boilers and Industrial Furnaces Using Hybrid-type Hydrogen Gas Supply System

Hiroshi IMAYO[*1] ・ Koji TANAKA[*2] ・ Kiminobu KAGAWA[*3] ・ Dr. Akira MATSUOKA[*4] ・ Kazuki MURAKAMI[*4] ・ Dr. Akitoshi FUJISAWA[*4]

[*1] New Business Planning Department, New Business Development Division, Machinery Business (currently Compressor & Static Equipment Engineering Department, Compressor & Static Equipment Unit, Machinery Business)
[*2] Business Development Department (currently Technology Strategy & Planning Department)
[*3] New Business Promotion Section, Engineering Business
[*4] Mechanical Engineering Research Laboratory, Technical Development Group

Abstract

CO_2-free hydrogen is attracting attention as a decarbonization measure. In transitioning to a hydrogen society, the use of hydrogen in a local production for local consumption model, utilizing electricity derived from renewable sources for on-site production and utilization of hydrogen, is a realistic solution until a large-scale hydrogen supply infrastructure is established. However, electricity derived from renewable sources faces the challenge of ensuring a stable hydrogen supply. To counter this, Kobe Steel is developing and demonstrating a hybrid hydrogen gas supply system that combines two hydrogen supply sources: hydrogen derived from renewable energy sources and stored liquid hydrogen.
In addition, it is more realistic for facilities that use hydrogen to convert fuel while making the most of existing equipment rather than undergoing large-scale modifications or renovations. Therefore, in transitioning to a hydrogen society, it is important to consider how to start a realistic hydrogen supply and utilization system from the perspectives of both hydrogen suppliers and users. Kobe Steel's Takasago Works strives to realize a hydrogen society by demonstrating a series of steps, from hydrogen production and supply to hydrogen use in boilers and heating furnaces.

Introduction

In October 2020, the Ministry of Economy, Trade and Industry (METI, an agency of the Japanese government) declared a goal of achieving carbon neutrality by 2050 by reducing greenhouse gas emissions to net zero. METI then released the Basic Hydrogen Strategy in June 2023 to provide direction on accelerating the transition to a hydrogen-based society and on strengthening the competitiveness of the hydrogen industry.[1)] This Strategy also sets targets for hydrogen supply costs at 30 JPY/Nm^3 by 2030 and 20 JPY/Nm^3 by 2050. As part of these efforts, advancements are being made in hydrogen production in Australia. For instance, the country completed the world's first large-scale maritime transport of liquid hydrogen to Japan via liquefied hydrogen carrier in February 2022.

Currently, about 90% of primary energy supplied in Japan comes from fossil fuels, with about 40% consumed as thermal energy. Furthermore, roughly 40% of this thermal energy is used in the industrial sector. The decarbonization of not only electric power, but also thermal energy, is thus a key challenge in achieving carbon neutrality. Switching to CO_2-free fuels is one means of decarbonizing thermal energy. This paper focuses on hydrogen, regarded as a promising CO_2-free fuel. Section 1 explains the justification for this area of focus. CO_2-free hydrogen includes green hydrogen and blue hydrogen. Green hydrogen is produced using electricity from renewable energy sources via water electrolysis equipment (hereafter, electrolyzers). Blue hydrogen describes the capture and subsequent storage or reuse of by-product CO_2 produced when fossil fuels are reformed, which reduces carbon emissions. One challenge in achieving the aforementioned goal lies in securing green hydrogen. Electric power from renewable energy is not yet widely available in Japan, making procurement difficult. Furthermore, green hydrogen is significantly more expensive than the typical fuels such as city gas. Efforts such as those described above in Australia should make it possible to economically import blue hydrogen into Japan as liquid hydrogen, although this is not expected to come to fruition until the 2030s or later. Because the industrial sector needs a stable energy supply, it cannot easily switch to CO_2-free hydrogen fuel yet, as the supply infrastructure is not in place.

This paper proposes a hybrid-type hydrogen gas supply system (Section 2) as a concrete strategy for gradually expanding hydrogen supply and utilization. The system starts with the production of green hydrogen derived from renewable energy using an on-site electrolyzer (**Fig. 1**). Once the stable supply of economical liquid hydrogen is established, green or blue hydrogen will be incorporated as an input to the system.

Kobe Steel's Takasago Works in Takasago City, Hyogo Prefecture, is a production base for materials business divisions (e.g., cast and forged steel, titanium, iron powder) and machinery

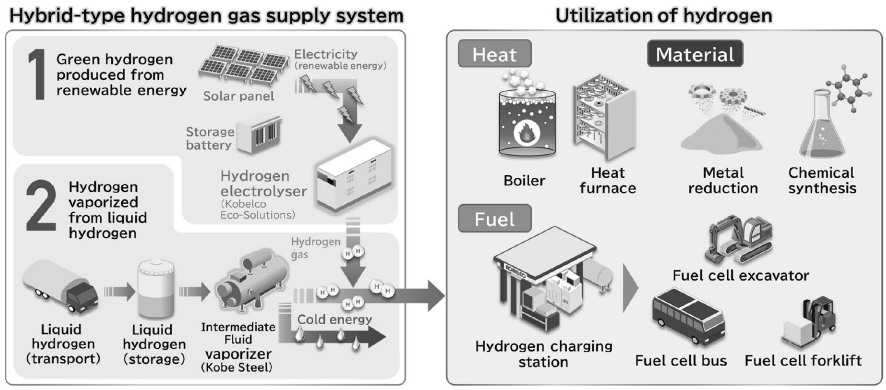

Fig. 1 Hybrid-type hydrogen gas supply system

business divisions (e.g., energy-related equipment). Therefore, we must switch from fossil fuels to CO_2-free fuels in our numerous boilers and heating furnaces alongside providing products and technologies that contribute to our customers' decarbonization efforts. Kobe Steel is combining the technologies and products of Kobelco Eco-Solutions Co., Ltd. and Kobelco E&M Co., Ltd. to conduct studies and demonstration tests on hydrogen utilization in a way that involves collaboration between the users of hydrogen and the producers of hydrogen.[2)]

1. Hydrogen utilization potential at Takasago Works

Many companies have initiated CO_2 reduction efforts. For instance, Power Purchase Agreements (PPAs) are gaining attention as a means to advance carbon-neutral electricity through the use of renewable energy. PPAs set the conditions for an arrangement in which a third-party power provider installs renewable energy equipment (e.g., solar panels) on the customer's premises and the customer pays the provider for the electricity consumed. However, electrification is difficult for industrial furnaces operating in the high-temperature range of 800 to 900℃ and above. One challenge associated with such equipment is the thermal resistance of recirculation fans. As such, one measure of decarbonization to advance carbon-neutral thermal energy is to switch to CO_2-free fuels such as hydrogen or ammonia.

Which CO_2-free fuel will prevail remains to be seen, but four factors point to the conversion to hydrogen fuel as promising for the industrial sector. 1: There have been advances in hydrogen burner technology, and there are already hydrogen boilers on the market. 2: Hydrogen has various uses outside of fuel. 3: Hydrogen can support energy security owing to its multiple procurement avenues (production via electrolysis using regionally sourced renewable energy, blue or green hydrogen from overseas, and regional by-product hydrogen). 4: Ammonia is a toxic gas. Therefore, while it can be used where people can be distanced from a leak (e.g., power plants in coastal areas), the danger associated with leakage is high for inland plants. Further, the dehydrogenation of MCH (methylcyclohexane) is highly energy intensive.

Kobe Steel's Takasago Works operates over 100 boilers and heating furnaces across multiple material and machinery production sites. These pieces of equipment have varying combustion capacities and operating patterns (continuous, intermittent, load fluctuations during operation, etc.). As such, our research examines hydrogen supply and utilization models suitable for multiple locations and a wide variety of hydrogen utilization points. These studies thus have value not only in our own transition to carbon neutrality, but also in this transition among production sites across various industries throughout Japan. Therefore, we assessed the potential for using CO_2-free hydrogen (including various hydrogen carriers such as ammonia and MCH) at each of our sites based on the energy demand of our boilers, heating furnaces, metal reduction equipment, industrial vehicles, etc. We also established a comprehensive model for the procurement, storage, supply, and utilization of CO_2-free hydrogen and calculated the applicable costs. Furthermore, we identified challenges to expanding hydrogen utilization and researched solutions to these challenges.[3)]

Calculations show ammonia as the most economical option in terms of both hydrogen carrier procurement and consumer receiving terminals, and thus the most economical option within the hydrogen utilization model. However, as mentioned earlier, ammonia poses risks for inland plants. The technological readiness level of liquid hydrogen for transport and storage is lower than that of ammonia.

However, the significant potential for the costs associated with liquid hydrogen to decline could shrink the difference in cost between ammonia and liquid hydrogen. Selecting the optimal hydrogen carrier also depends highly on the regional import policies for hydrogen carriers applicable to the plant location. Kobe Steel's Takasago Works is in the Kobe/Kansai region, where there is ongoing discussion regarding the establishment of a hydrogen supply chain. In anticipation of growth in the hydrogen supply chain, we are investigating converting to hydrogen for thermal energy in our plants.

2. Producing hydrogen

The method of hydrogen delivery must be based on demand patterns and levels and on the progress of fuel conversion. For example, while racks of hydrogen cylinders are an adequate means of supplying hydrogen to a few fuel cell forklifts, this method would be unsuitable for supplying hydrogen as fuel to boilers or heating furnaces. Such cases necessitate plumbed hydrogen gas or large-scale supply facilities, such as liquid hydrogen satellite bases (facilities that store liquid hydrogen and supply it to plants as needed). However, in the early stage of transitioning to hydrogen, high hydrogen prices and inadequate supply infrastructure will likely mean that only a limited number of plants will use hydrogen. This period of low hydrogen demand will see little progress in the construction of large-scale hydrogen production and supply facilities. As such, cost reduction for the supply infrastructure will stagnate, potentially in turn stagnating the conversion to hydrogen for fuel. Therefore, in establishing the hydrogen supply chain, hydrogen demand must grow in tandem with the construction of hydrogen supply infrastructure. The stepwise expansion of hydrogen demand will promote the fuel transition over the medium to long term.

The only liquid hydrogen currently available in Japan is gray hydrogen produced by reforming LNG, and the import of inexpensive CO_2-free hydrogen is not expected to reach full-scale operation until the 2030s or later. It will likely be even later before the hydrogen supply chain is sufficiently developed to support inland utilization. Until that point, the most realistic option during the introduction phase of the transition to hydrogen is to produce and use hydrogen locally. This model uses local renewable energy from sources such as electrolysis and solar power to produce and use green hydrogen on site. On-site hydrogen production equipment can convert surplus renewable energy into hydrogen for storage and utilization. This is a promising solution for coordinating the supply and demand of renewable energy in conjunction with fluctuations related to both location and time.

As hydrogen utilization increases over time, hydrogen derived from renewable energy alone will likely be insufficient to meet demand, necessitating supplementation with liquid hydrogen. Even if it becomes possible to import CO_2-free liquid hydrogen, it would be exceptionally costly for every plant to have its own facility for liquid hydrogen storage, regasification, and supply, inhibiting widespread adoption. Therefore, liquid hydrogen facilities shared by multiple plants or industrial parks should reduce the burden on individual companies and facilitate the expansion of hydrogen utilization.

As described above, the expansion of demand and the construction of supply facilities must occur in tandem for a successful hydrogen supply chain. A promising hydrogen introduction plan begins with supporting hydrogen utilization by using regional renewable electricity for on-site hydrogen production via electrolysis. Hydrogen shortages will be supplemented with domestic gray hydrogen or other liquid hydrogen. The switch to domestic and imported green hydrogen for liquid hydrogen will occur in a later phase. The next section provides an overview of the hybrid-type hydrogen gas supply system, which is designed around the early stage of the hydrogen supply chain, and details the system's products and technologies.

2.1 Overview of the hybrid-type hydrogen gas supply system

Kobe Steel has begun technological development and demonstration tests on its hybrid-type hydrogen gas supply system[4)], which is a combination of two supply systems: a hydrogen production process that uses electrolysis powered by renewable electricity, and a regasification process for stored liquid hydrogen. An operation management system connects the two supply systems for optimized control. This system supports a hydrogen supply process that addresses both the initial phase of hydrogen utilization (introduction phase) and the subsequent phase when hydrogen utilization expands (expansion phase). The explanation that follows illustrates how Kobe Steel envisions the model for the hydrogen supply process.

In the introduction phase, there is not yet a stable and economical supply of CO_2-free liquid hydrogen. Therefore, hydrogen comes from electrolyzers capable of producing CO_2-free hydrogen using renewable electricity. Since stable plant operation is the top priority, the reliability and ease of operation of the electrolyzers are particularly critical during this phase. On-site renewable electricity is unstable because it is weather dependent, presenting a challenge to ensuring sufficient electricity for an electrolyzer. Therefore, it is important to charge the battery when renewable electricity exceeds demand and to draw power from the grid (e.g., by using renewable energy certificates or electricity during cheaper time periods) when renewable electricity is insufficient. This is why we developed an operation management system, which provides power control functions to ensure stable and economical power while maximizing the electrolyzer's utilization of renewable energy. Section 2.1.3 details this system.

During the expansion phase, since the supply of CO_2-free liquid hydrogen will be established, the hydrogen supply system will be upgraded to use both liquid hydrogen and hydrogen from electrolyzers to accommodate the increase in hydrogen utilization by the plants. Using stored liquid hydrogen to adjust supply rates is a simple solution for overcoming the instability of CO_2-free hydrogen produced by electrolyzers. In addition, the cold energy generated during liquid hydrogen regasification can be used for cooling production plant equipment, air conditioning systems, heat pumps, and similar applications to improve process efficiency and reduce energy consumption. In addition, the combined use of hydrogen from electrolyzers and liquid hydrogen makes it possible to capitalize on liquid hydrogen procured from overseas alongside hydrogen from electrolyzers that are located domestically and are powered by domestically produced energy. This strengthens our local energy security.

When using both hydrogen from electrolyzers and liquid hydrogen, balancing the supply of each with overall hydrogen gas demand is crucial. This is why our operation management system will have control functionality to selectively minimize running costs or CO_2 emissions according to customer needs. This function will account for CO_2 emissions intensity, the unit price of grid electricity for powering the electrolyzer, and the unit price of liquid hydrogen.

In March 2023, we completed construction of a demonstration facility for the hybrid-type hydrogen gas supply system, where demonstration tests are underway. **Fig. 2** shows the facility, and **Fig. 3** shows its flow diagram. The HHOG® (detailed in Section 2.1.1), manufactured by Kobelco Eco-Solutions Co., Ltd., is the electrolyzer. Kobe Steel's Intermediate Fluid Vaporizer (detailed in Section 2.1.2) serves as the liquid hydrogen vaporizer. The facility's renewable energy power generation system comprises a photovoltaic system (detailed in Section 2.1.1) and a battery bank. The EPC (engineering, procurement, and construction) of this facility was handled by Kobelco E&M Co., Ltd., which has amassed expertise in all types of hydrogen-related technology through its abundant experience in constructing hydrogen stations. The following sections detail the facility's main equipment and operation management system.

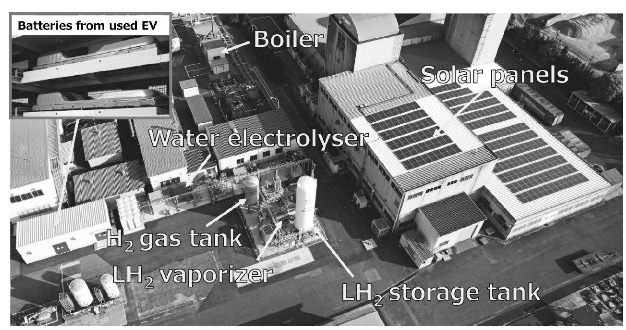

Fig. 2 Hybrid-type hydrogen gas supply system demonstration facility (Takasago Works)

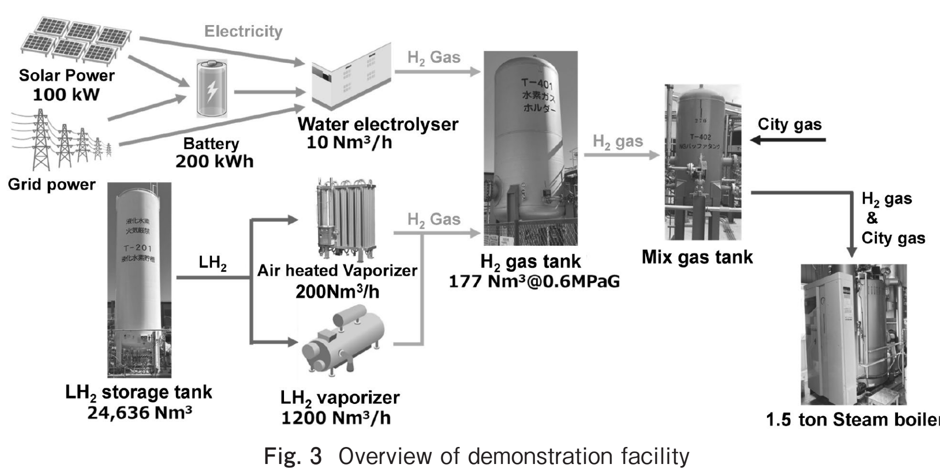

Fig. 3 Overview of demonstration facility

2. 1. 1 Electrolyzer powered by renewable energy

Kobelco Eco-Solutions Co., Ltd. has been working on the technological development of the HHOG® (High-purity Hydrogen and Oxygen Generator) electrolyzer, which uses a polymer electrolyte membrane.

While we have primarily supplied industrial process gases for production in industries such as electronics and metalworking, the use of hydrogen produced using renewable energy sources (e.g., solar and wind-power generation) has recently gained attention as a means of achieving carbon neutrality. As a result, hydrogen now sees widespread use in energy applications such as hydrogen stations, fuel cells, and hydrogen boilers.

Electrolyzers require several utilities including municipal water, electricity, nitrogen gas, coolant, and compressed air for instrumentation. When these utilities are not available near the operating site, customers face the challenge of setting up utilities in addition to the electrolyzer itself. This led us to release the "all-in-plan" unit in March 2023, which eliminates the need for all utility connections except water and electricity.

The demonstration unit of the all-in-plan unit completed standalone trial operation before being relocated to Kobe Steel's Takasago Works for the demonstration test of the hybrid-type hydrogen gas supply system. Long-term demonstration testing will validate its reliability during the summer and winter seasons and provide a means for potential customers to observe the system operating under solar power before introducing it in their operation.

The nominal maximum output of the demonstration facility's photovoltaic system is 105 kW, which is approximately twice the demonstration electrolyzer's full-load power consumption of 50 kW. Solar power systems generate a highly variable amount of power during the day based on how the panels are installed, sunlight intensity, and the position of the sun. **Fig. 4** shows a sample of the variation in solar power production over time during the demonstration. Overcast conditions and nighttime hours limit power generation, whereas peak output is extremely high in clear daytime weather. Therefore, ensuring the full-load power consumption of the electrolyzer is less than the maximum output of the photovoltaic system increases the proportion of renewable energy used even during periods of low generation.

Specifically, the power generated on sunny days exceeds the demand of the electrolyzer, resulting in the generation of surplus power, whereas on cloudy days, power generation decreases significantly and may fall below the demand of the electrolyzer. Furthermore, there is an overall decrease in power generation in the winter because of the low position of the sun, which results in a poor angle of incidence on solar panels. Thus, solar power is highly prone to seasonal and weather variation, making it an unstable power source for electrolyzers. This again illustrates the importance of establishing a reliable, economical supply of low-carbon hydrogen by combining unstable solar power with municipal and battery power as backups based on the weather and time of day alongside liquid hydrogen regasification. Our operation management system, covered in Section 2.1.3, is the control system that satisfies this need.

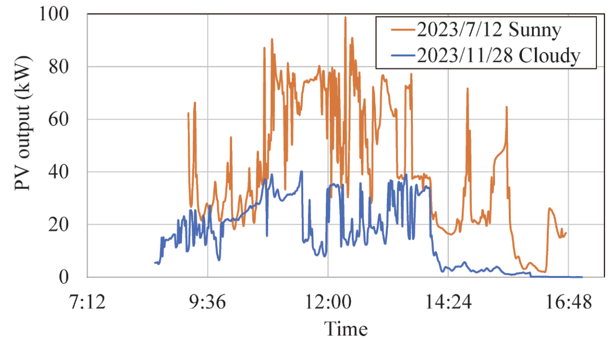

Fig. 4 Typical examples of solar power production

2. 1. 2 Cryogenic intermediate liquid hydrogen vaporizer

The "Large-scale Hydrogen Supply Chain Establishment" project, which is part of the Green Innovation Fund Projects, is examining the import of CO_2-free hydrogen from overseas. Hydrogen is unsuitable for transport in gaseous form because of its extremely low density. Therefore, research into the maritime transport of hydrogen in liquid form is underway. In this state, hydrogen is cooled to -253℃ and reduced to 1/800 of its gaseous volume. Imported liquid hydrogen is stored in vacuum-insulated cryogenic double-wall tanks and then vaporized as needed for supply. Liquefying hydrogen gas is highly energy intensive. Recovering and utilizing cold energy given off during regasification conserves energy and reduces CO_2 emissions. If hydrogen is used in large quantities for purposes such as hydrogen power generation, the recovery and utilization of cold energy from liquid hydrogen will be essential.

Kobe Steel is a leading manufacturer of liquefied natural gas (LNG) vaporizers, with a strong track record of supplying this equipment all over the world. Our lineup includes the Intermediate Fluid Vaporizer (IFV), which is well suited for recovering cold energy during regasification.

We used the technology cultivated in developing LNG vaporizers to develop an IFV-type liquid hydrogen vaporizer under a grant from the New Energy and Industrial Technology Development Organization (NEDO).[5] For details, see "Demonstration Tests of Three Types of Liquid Hydrogen (LH_2) Vaporizers" on p.22 of this issue.

2. 1. 3 Operation management system for monitoring and controlling hydrogen production and utilization

The operation management system balances the supply of hydrogen gas between vaporized liquid hydrogen and hydrogen produced by an electrolyzer with three power sources (solar, battery, grid power). Managing the power source of the electrolyzer curtails carbon emissions and hydrogen supply costs. Thus, this system ensures a stable supply of hydrogen gas by controlling two hydrogen supply sources such that they complement each other based on hydrogen demand. Our system performs automatic operation, control, and monitoring based on a pre-established supply plan. Inputs to the supply plan include the following day's projected demand, weather factors, consumption rate, and operating mode. Parameters managed by the system include the balance of the electrolyzer's power supply sources as well as the amounts of hydrogen produced and vaporized. Described next are the results of the system's demonstration and plans for system enhancements.

We conducted a demonstration of our system that balances the power source of the electrolyzer based on a supply plan. **Fig. 5** shows the electrolyzer's operating data from this demonstration. As described in Section 2.1.1, the full-load power consumption of the electrolyzer (50 kW) is less than the maximum output of the solar power generation system (105 kW). Therefore, we configured the demonstration facility such that the battery stores surplus power when solar power generation exceeds electrolyzer demand; the battery is discharged as a backup power source when solar power generation is insufficient; and power is supplied from the grid if there is still a deficit. Thus, the battery and power grid compensate for the instability of renewable energy to ensure stability of the power supply to the electrolyzer. The system also includes functionality to manually prioritize the electrolyzer's power sources (solar power, battery, grid power). Although the default settings prioritize renewable energy for maximum reduction of carbon emissions, it is possible to prioritize grid power during periods of low electricity costs for economy. As shown in Fig. 5, periods of surplus power generation are characterized by the storage of power in the battery, and periods when solar power alone is insufficient for the electrolyzer are characterized by power discharging from the battery as second priority. If the battery level falls below the lower limit, power is drawn from the grid as the third-priority source, ensuring stable operation of the electrolyzer at rated power.

The demonstration facility also has a screen enabling real-time monitoring of hydrogen production, storage, and supply as shown in **Fig. 6** as part of an operation monitoring system. The system calculates the cost and carbon emissions of the hydrogen supplied and can output this data as daily and monthly reports. This simplifies the monitoring of carbon emissions from hydrogen supply plants. It also enables data-driven decision-making for capital investments in electrolyzers, liquid hydrogen equipment, renewable energy equipment, and similar technologies in conjunction with the expansion of hydrogen use by elucidating the cost structure (e.g., costs for grid power and liquid hydrogen).

At a later time, we will demonstrate the supply planning function we are developing. This function

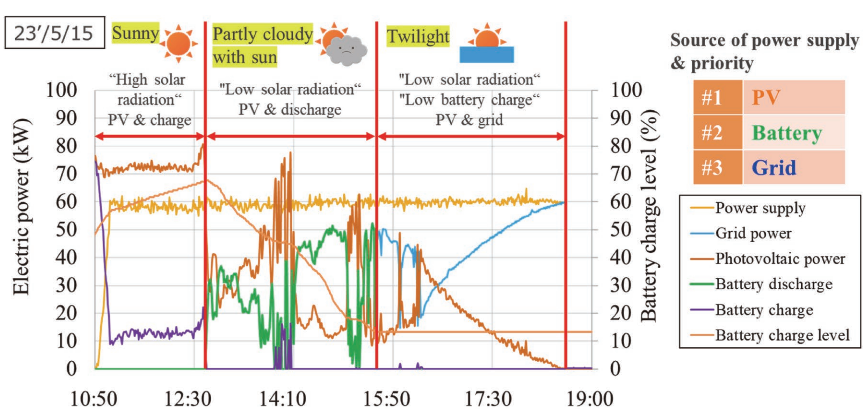

Fig. 5 Examples of power supply to electrolyzer

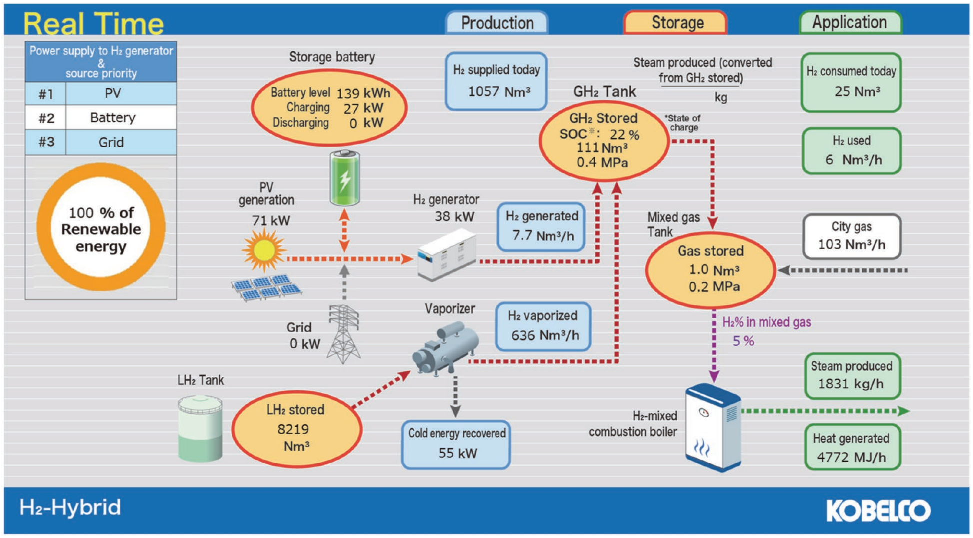

Fig. 6 Real-time monitor of operation management system

automatically produces a hydrogen supply plan based on hydrogen demand values entered in advance and controls hydrogen supply equipment based on the mode selected (CO_2 reduction priority or cost priority). The hydrogen supply planning function plans battery charging and discharging operations based on solar power generation prediction technology that uses sunlight intensity forecast data. This ensures sufficient storage capacity for when the predicted sunlight intensity is high, minimizing excess solar power generation. Furthermore, by predicting the daytime draw from the power grid, this function minimizes consumption during the day by discharging only the necessary amount of inexpensive electricity stored during nighttime hours. Additionally, the system has a function to calculate the balance daytime storage capacity with nighttime storage amount to preferentially minimize either carbon emissions or costs.

3. Hydrogen utilization

Recent years have seen the commercialization of pure hydrogen boilers and hydrogen co-firing boilers for hydrogen utilization as well as progress in the development of hydrogen burners for industrial furnaces. However, promoting the transition to hydrogen for fuel is difficult because the industrial sector prioritizes stable operation and cost reduction. Problematically, the early stage of adoption is characterized by an unstable hydrogen supply chain and significant costs. To overcome this challenge, it is important to leverage existing facilities to gradually expand hydrogen utilization and thereby reduce capital investment requirements. Following are our proposed strategies

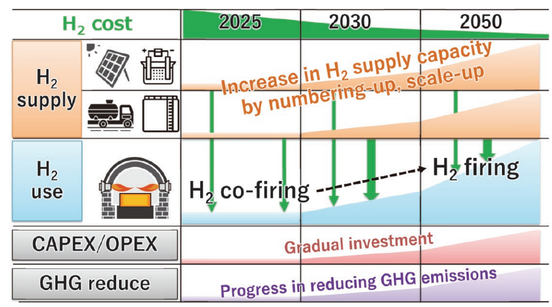

Fig. 7 Overview of phased fuel conversion scenarios

for transitioning existing facilities to hydrogen fuel in support of hydrogen utilization.

Municipal gas in Japan is assigned a designation based on its specifications. "City gas 13A," a common type of municipal gas, has a different heat value, maximum combustion potential, and flame temperature than hydrogen. Therefore, completely switching from city gas 13A to hydrogen renders current equipment obsolete because it must be replaced by burners and other components capable of hydrogen combustion. Therefore, as shown in **Fig. 7**, co-firing city gas 13A with hydrogen could be a realistic option for a phased fuel conversion during the introduction phase of hydrogen. A blending ratio of hydrogen in city gas 13A of about 20 vol% maintains the standard combustion characteristics range for city gas 13A[6)], in which case hydrogen co-firing is considered feasible even in combustion equipment with burners designed for city gas 13A.

Hydrogen co-firing with existing combustion equipment enables operations to revert to city gas if the hydrogen supply becomes unstable, thereby maintaining production activities. This is an effective means of hydrogen utilization for the introduction phase.

During the subsequent hydrogen expansion phase, it is realistic to gradually introduce combustion equipment with hydrogen burners. In this case too, plants can hedge their operational risk by keeping their current equipment while using the new equipment designed for use with hydrogen. However, many plants will likely not have sufficient footprint for multiple sets of equipment, necessitating a fuel transition plan that accounts for equipment swap-out.

Kobe Steel's Takasago Works has approximately 100 boilers and industrial furnaces with varying combustion capacities that serve as hydrogen utilization points. We are conducting demonstration tests to verify the feasibility of using hydrogen in existing city gas boilers and industrial furnaces, as well as heating characteristics and the effects of hydrogen on heated materials when switching to hydrogen combustion.[7)]

3.1 Hydrogen utilization in combustion boilers

Small once-through boilers are widely used in factories. Although they are already available in pure hydrogen-fueled models, securing a reliable supply of hydrogen will be a challenge in the early stages of their adoption. For example, operating one pure hydrogen boiler with an evaporation rate of 2 tons/h at rated capacity requires approximately 400 Nm^3/h of hydrogen. Until there is a stable and economical supply of CO_2-free liquid hydrogen, CO_2-free hydrogen must be produced on site. Specifically, a large electrolyzer capable of producing 400 Nm^3/h of hydrogen is required, and thus renewable power equipment within the 2-MW class (based on an electrolyzer power consumption of 5 kW/Nm^3). The solar park capable of this demand requires a footprint of approximately 10,000 m^2 (roughly the size of the playing field inside the Tokyo Dome), which most plants would find difficult to secure. Even if solar panels could be installed, their average annual operating rate is only about 15%. To produce a stable supply of hydrogen for the boiler, renewable electricity must be procured from the grid. Plants controlling multiple small once-through boilers would need even more additional equipment. Consequently, there is likely a limited number of plants capable of introducing pure hydrogen boilers.

While securing a stable supply of hydrogen presents challenges, as mentioned earlier, even plants without a guaranteed supply of hydrogen from renewable energy can reduce carbon emissions through hydrogen co-firing in existing city gas boilers. Therefore, it is necessary to clarify the challenges involved in hydrogen co-firing with city gas boilers. This spurred the execution of hydrogen co-firing tests using existing small, city gas-fired once-through boilers.[8)]

Fig. 8 shows the layout of the hybrid-type hydrogen gas supply system demonstration facility and the boiler at Kobe Steel's Takasago Works. The system mixes city gas and hydrogen at a set ratio and supplies the mixture to the boiler. The boiler used is a Samson Co., Ltd. NFBS-1500PN, a small, city gas-fired once-through boiler with an equivalent evaporation of 1.5 ton/h. The operating load of the boiler is controlled using a three-position control system: high-combustion mode, low-combustion mode, and stop. The boiler has a nozzle-mix burner, meaning fuel and air are supplied separately and mix at the burner tip for combustion.

City gas and propane are supplied to consumers at a consistent composition by gas retailers. By contrast, with hydrogen co-firing, the consumer is responsible for the mixture of city gas and hydrogen in the system the boiler is part of. A hydrogen mixing ratio that fluctuates during boiler operation can cause a deviation from optimal combustion conditions, potentially leading to issues such as incomplete combustion or increased NOx emissions. Therefore, it is critical to maintain a constant hydrogen mixing ratio.

Fig. 9 shows an overview of the hydrogen mixing system in this demonstration facility. The system uses cascade control, meaning the flow rates of hydrogen gas and city gas into the tanks vary based on the difference between the actual and setpoint pressures of the mixed gas tank (city gas/hydrogen). Setpoints for the hydrogen gas flow sensor (QH) and city gas flow sensor (QC) are configured to constantly maintain a predetermined mixing ratio α of city gas to hydrogen. Since city gas and hydrogen have different heat values per unit volume, the mixing ratio can be calculated from the heat value of the mixed gas. The tank outlet has a calorimeter to monitor the hydrogen mixing ratio.

Fig.10 shows the time-dependent change in mixed gas flow rate and heat value during operation

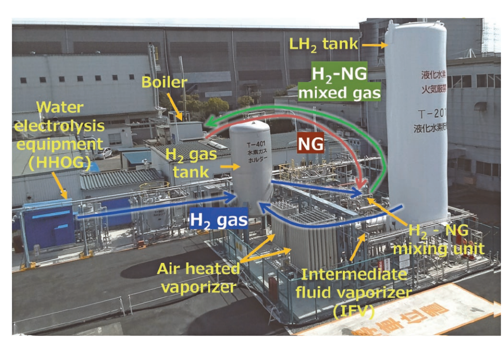

Fig. 8 Demonstration facility and small once-through boiler

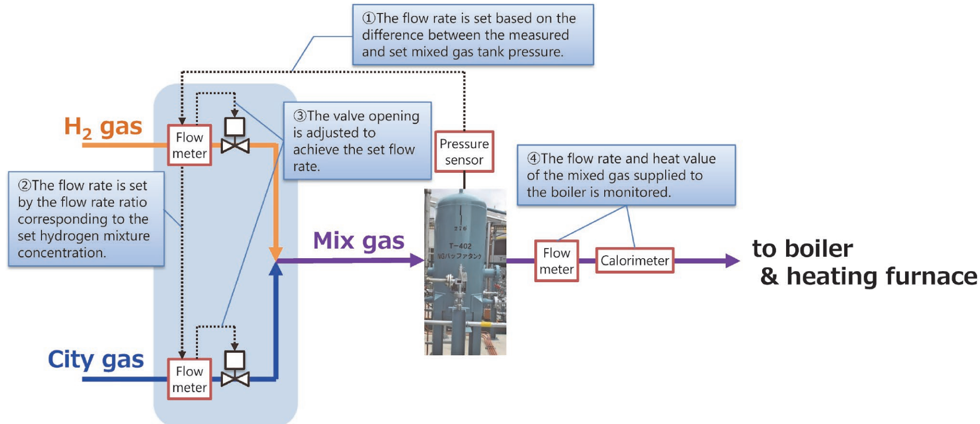

Fig. 9 Overview of hydrogen mixing system

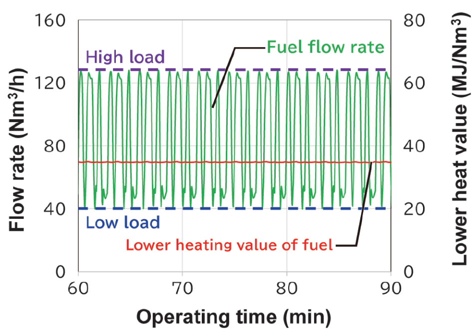

Fig.10 Evaluation of supply stability of 30 vol% H_2 mixed gas

Table 1 Comparison of boiler performance at various H_2 conc.

H_2 conc.	0%	10%	20%	30%
Boiler efficiency [%]	91.3	90.3	90.7	90.5
Exhaust gas NOx conc. [ppm, 5%-O_2]	48.5	46.2	47.9	47.0
Exhaust gas O_2 conc. [vol%]	3.8	3.3	3.7	3.6

with a 30 vol% hydrogen mixture and fluctuating boiler load. Although the flow rate of the mixed gas fluctuates in response to changes in boiler load, its heat value remains constant. We confirmed that our hydrogen mixing system can supply mixed gas at a constant ratio of city gas to hydrogen even when boiler load and fuel gas consumption vary.

Table 1 shows boiler performance during rated load operation for hydrogen concentrations from 0 to 30 vol%. At all hydrogen concentrations, boiler efficiency was equivalent to that of pure city gas combustion. The exhaust gas characteristics, including NOx and O_2 concentrations, were also comparable. The maximum NOx concentration in this boiler remained below the limit of 60 ppm (equivalent to 5% O_2 concentration) stipulated in the agreement with the municipality.

This demonstration confirmed that hydrogen co-firing up to 30 vol% is feasible even in city gas boilers. However, the effects of increased flame temperature due to hydrogen co-firing and the potential for long-term deterioration of components such as burners and boiler shells requires further testing. Furthermore, these results are based on tests conducted using a specific manufacturer's boiler. It is necessary to confirm with each boiler manufacturer whether their boilers are capable of hydrogen co-firing. Ongoing discussions with major once-through boiler manufacturers reveal differing opinions regarding the feasibility of hydrogen co-firing in city gas boilers. However, boiler manufacturers are working to accommodate hydrogen co-firing, such as by developing hydrogen co-firing boilers [9] and producing components for retrofitting to enable hydrogen co-firing in city gas boilers.[10] We will continue corresponding with boiler manufacturers to explore reasonable methods for initiating and expanding hydrogen utilization from both the supply and usage perspectives.

3.2 Hydrogen utilization in heating furnaces

Fig.11 shows the distribution of heating furnace capacities at Kobe Steel's Takasago Works. Most heating furnaces at this facility have a combustion capacity of 1 – 3 MW, which is likely representative of heating furnaces in Japan in general. Therefore, we are first investigating a fuel conversion to hydrogen in 2-MW-class heating furnaces and are conducting demonstration tests using existing Kobe Steel furnaces and new test furnaces. The two types of demonstration tests are described next.

Section 2 presented a phased fuel conversion scenario. However, since it will take time to secure a stable and economical supply of hydrogen, it is crucial to begin hydrogen utilization in the early stages of fuel conversion by using existing furnaces through hydrogen co-firing rather than pursuing replacement with pure hydrogen furnaces at the outset. Achieving a combustion capacity of 2 MW using pure hydrogen requires a hydrogen supply of 667 Nm³/h (based on hydrogen's lower heating

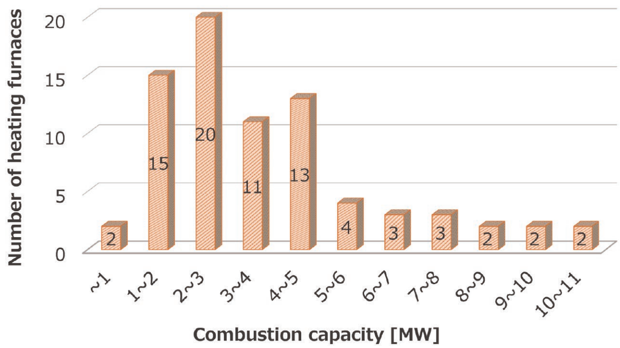

Fig.11 Distribution of combustion capacity of heating furnaces

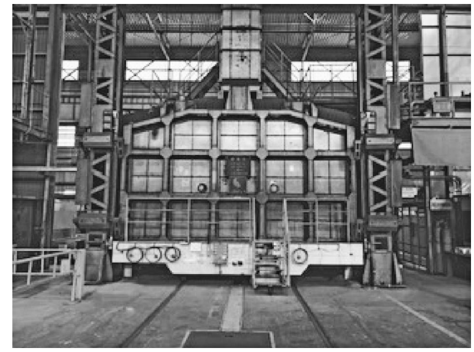

Fig.12 Heating furnace scheduled for modification

value of 10.8 MJ/Nm^3). Given the lack of a stable and economical supply of hydrogen in the early stage of the transition, stable operation will likely be difficult. Additionally, the use of existing heating furnaces makes it possible to continue furnace operation by reverting to city gas upon hydrogen supply insecurity. Therefore, we are conducting hydrogen co-firing and pure hydrogen combustion tests at Kobe Steel's Takasago Works using an existing heating furnace that has been in operation for nearly 50 years (**Fig.12**). The objective of this test series is to determine what hydrogen co-firing ratio is feasible without modifications and what modifications are necessary for pure hydrogen combustion.

Hydrogen will differ greatly from a given heating furnace's current fossil fuel (e.g., city gas) in terms of the combustion characteristics (maximum combustion potential, flame temperature) and the composition of the combustion atmosphere (e.g., vapor pressure of water), a critical consideration when converting the fuel in a heating furnace to hydrogen. Particularly in direct-fired furnaces, in which the product (the item being heated) is exposed to a high-temperature hydrogen combustion atmosphere, it is essential to thoroughly investigate the effect on the product's quality (scaling, decarburization, hydrogen content) and thermal characteristics (heat transfer rate/temperature distribution). As such, we installed a new 2-MW-class hydrogen demonstration furnace at Kobe Steel's Takasago Works for detailed data analysis into combustion characteristics, thermal characteristics, and the effect on product quality during hydrogen co-firing and pure hydrogen firing.

Kobe Steel has more than 500 heating furnaces across all sites, including Takasago Works. These furnaces cover a broad spectrum of specification sets because they have varying combinations of processing temperatures, heating methods, and types of metal heated. Therefore, although our demonstration tests target 2-MW-class direct-fired furnaces, we are pursuing technological development that applies to a multitude of conditions (e.g., by developing combustion simulations and material evaluation technologies).

By conducting demonstrations from both the hydrogen supply and utilization perspectives, we are revealing and overcoming technological development challenges shared by both sides. This includes accumulating expertise on the responsiveness of the supply side (vaporizers, electrolyzers) to fluctuations in hydrogen demand on the utilization side (heating furnaces) and the effects of start-up and shutdown operations.

In addition to demonstration testing for fuel conversion using existing heating furnaces, demonstration testing for hydrogen co-firing and pure hydrogen firing in new test furnaces will yield insights into fuel conversion practices suitable for both the introduction phase and the expansion phase of hydrogen utilization. This should drive more widespread use of hydrogen in heating furnaces.

Conclusions

Achieving carbon neutrality requires the hydrogen supply side and the hydrogen utilization side to work in lockstep to build the hydrogen supply chain. Kobe Steel's Takasago Works operates boilers and industrial furnaces of various sizes. Therefore, identifying the challenges of fuel conversion to hydrogen and conducting studies and demonstrations to address these challenges contributes to our own carbon neutrality while revealing valuable insights and achievements supporting decarbonization in other industrial sectors that use thermal energy.

The KOBELCO Group's current Mid-Term Management Plan (FY2024 – 2026) delineates seven "X initiatives," collectively called "KOBELCO-X," as the transformations our Group must bring to fruition to evolve into an appealing enterprise. The hydrogen utilization efforts introduced in this paper are examples of AX and GX.

■AX (Ambidexterity: enhancing earning power and pursuing growth)

The machinery & engineering divisions (development of hybrid-type hydrogen gas supply system) and the materials divisions (hydrogen utilization in high-temperature furnaces) are collaborating to accelerate the demonstration of hydrogen utilization.

■GX (Green transformation：taking on the challenge of realizing carbon neutrality)

This transformation promotes decarbonization by advancing CO_2-free hydrogen supply technologies and promoting hydrogen utilization as thermal energy.

Finally, some of our results were obtained through the project "Development of Technologies for Realizing a Hydrogen Society" (JPNP14026), a grant program of the New Energy and Industrial Technology Development Organization (NEDO). We express our gratitude here.

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