Activities for Realization of International Liquefied Hydrogen Energy Supply Chain

Major advanced countries have been implementing hydrogen energy to achieve a decarbonized society. Japan, as the top runner, aims to commercialize a CO_2-free hydrogen energy supply chain, and starts operation of pilot demonstration project in 2020.

In the pilot project, the following technical demonstrations are making progress: hydrogen production from brown-coal in Australia, hydrogen land transportation from the production site, loading onto liquefied hydrogen carrier, the world's first long-distance marine transportation of large-volume liquefied hydrogen and liquefied hydrogen loading/unloading technology at the Port Terminal in Kobe. Outcomes of the present project will be a basis for future hydrogen supply that can link every corner of the world to Japan.

Introduction

In recent years, disasters caused by extreme climate frequently strike countries around the world including Japan, and CO_2 emission reduction has become an urgent issue common to all humankind. Since the Paris Agreement has come into effect, the world is striving to achieve net zero CO_2 emissions by the end of this century. Concrete planning and actions are absolutely necessary to achieve this goal. As an essential technology for such concrete actions, renewable energy has been standing in the limelight, but it is becoming clear that as more renewable energy is introduced, it becomes more difficult to secure a stable supply of electricity. Hydrogen is drawing attention as a clean energy because it can compensate for this disadvantage and contribute to energy security and environmental issues, and at the same time, can provide almost the same level of convenience as fossil fuels.

1 Background

(1) Japan's hydrogen strategies

The Strategic Roadmap for Hydrogen and Fuel Cells [1], a conglomeration of the knowledge of industry, academia, and government, was developed and released by Japan's Agency for Natural Resources and Energy in 2014, earlier than COP21 where the Paris Agreement was proposed. In addition, as a result of cross-ministerial collaboration, the Basic Hydrogen Strategy [2] specifies the roadmap further and was approved by Japan's Ministerial Council on Renewable Energy, Hydrogen and Related Issues in December 2017. Also, the fifth edition of Japan's Strategic Energy Plan, which was released in July 2018, has specific descriptions on hydrogen energy utilization [3].

Japan's target for CO_2 emission is a 26% reduction in fiscal 2030 from the fiscal 2013 level, and the Japanese Cabinet also decided on the long-term target of an 80% reduction by 2050 and a 100% reduction as quickly as possible after that. To achieve such ambitious goals, transition to low carbon energy is needed, and it is thought that hydrogen will play an especially important role in the energy transition.

Japan's Basic Hydrogen Strategy looks at hydrogen as a key future energy option on par with renewable energy, and promotes hydrogen utilization in every sector including transportation, electric power generation, industry, buildings and households. According to the strategy, the commercialization of hydrogen fueled power generation and the establishment of a liquefied hydrogen energy supply chain to support it will start in the early 2030s. With this in mind, we have been conducting technology development and demonstrations.

Japan has been leading the world in activities for such hydrogen energy utilization, but in recent years, more countries, both in the East and the West, are pursuing hydrogen utilization.

(2) Followers around the world

Hydrogen energy utilization is gathering momentum all over the world. The Hydrogen Council[4], which was established in January 2017 by 13 global companies from areas such as energy and resources, plants, industrial gases, and transportation equipment, aims to achieve a hydrogen-based society as quickly as possible and has 92 member companies as of the end of July in 2020, increasing by a factor of six times in the four years since its foundation. In addition, 70% of G20 countries have incorporated hydrogen utilization into their policies. In this way, there is a rapidly growing likelihood of realizing hydrogen utilization and its market expansion.

2 Concept of a CO_2-free hydrogen energy supply chain

We made our Concept of a CO_2-free Hydrogen Energy Supply Chain (CO_2-free Hydrogen Chains) public in our Medium-Term Business Plan in 2010, and ever since, we have been working on technology demonstrations toward commercialization and the establishment of a cooperative consortium as well as technology and product development to achieve that .

Figure 1 shows the concept of CO_2-free Hydrogen Chains in which hydrogen is produced by gasifying and refining brown-coal in Latrobe Valley, Victoria State, Australia, liquefied and then shipped to Japan in a liquefied hydrogen carrier. Brown-coal is low in transport efficiency due to its high moisture content and the spontaneous ignition that can occur when it dries. Because of this, it has only been used locally for power generation in the vicinity of the mine. Half of all the coal reserves in the world are brown-coal. Among them, Victoria State in Australia has a vast amount of those reserves, and the brown-coal reserves in the Latrobe Valley area alone are equivalent to 240 years' worth of electric power generation in Japan. The Loy Yang Coal Field shown in **Fig. 2**, which is said to be the

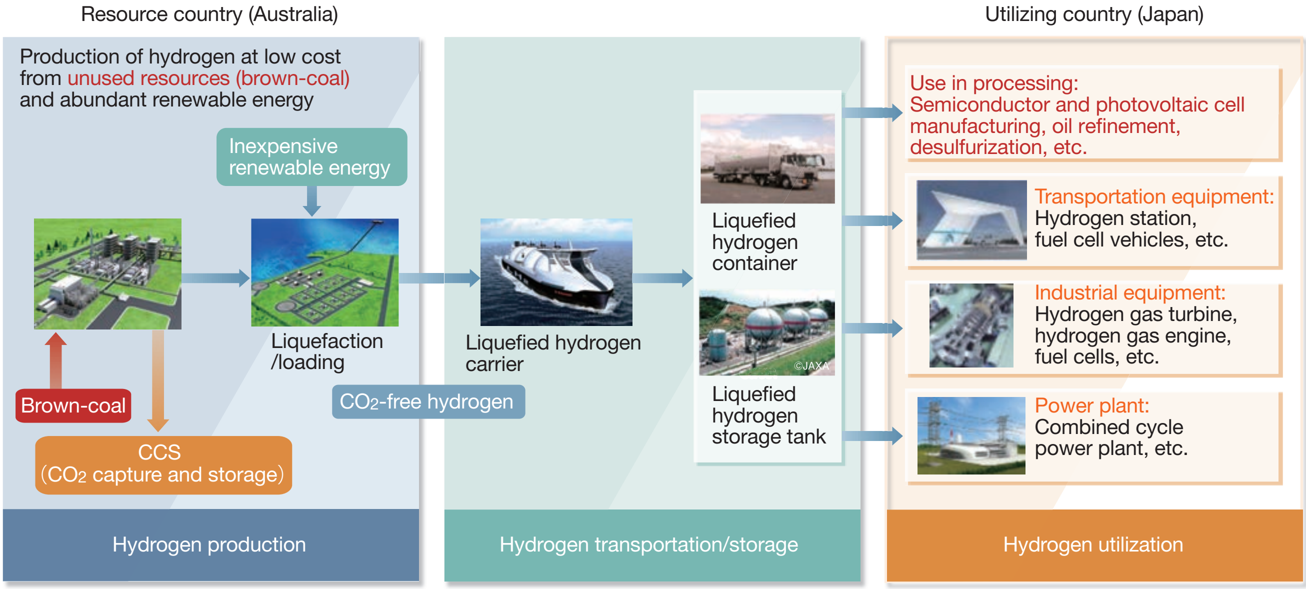


Fig. 1 Concept of CO_2-free Hydrogen Energy Supply Chains

Fig. 2 Loy Yang Coalfield in Latrobe Valley, Australia

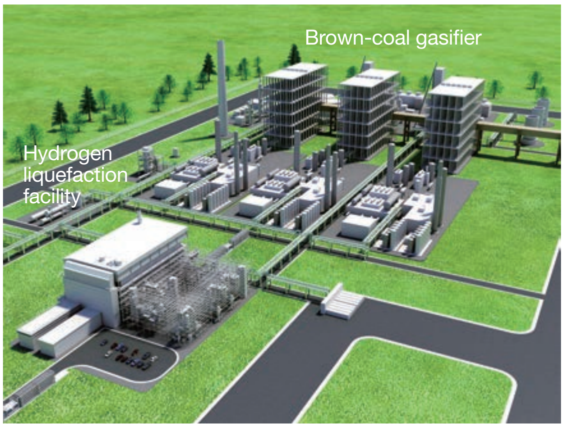
largest in the Southern Hemisphere, is an open-cut mine that boasts an astounding 14 km perimeter.

Hydrogen can be produced by gasifying and refining any fossil fuel, not just brown-coal, but in the refining process CO_2 is coproduced as well. By implementing carbon dioxide capture and storage (CCS) to capture the CO_2 byproduct at the site and store it underground, hydrogen can be obtained without releasing any CO_2 into the atmosphere (CO_2-free hydrogen). The Australian federal and the Victoria State governments are collaborating on a CCS project called CarbonNet, which makes Victoria State a good place to put both brown-coal and CCS to use [5]. The hydrogen produced in Latrobe Valley is compressed and transported through gas pipelines, and then liquefied in a hydrogen liquefier installed near a port. After being stored in a storage tank, the liquefied hydrogen is loaded onto a liquefied hydrogen carrier and shipped to Japan. This scale is equal to the liquefied natural gas (LNG) chain commercialized in the 1960s.

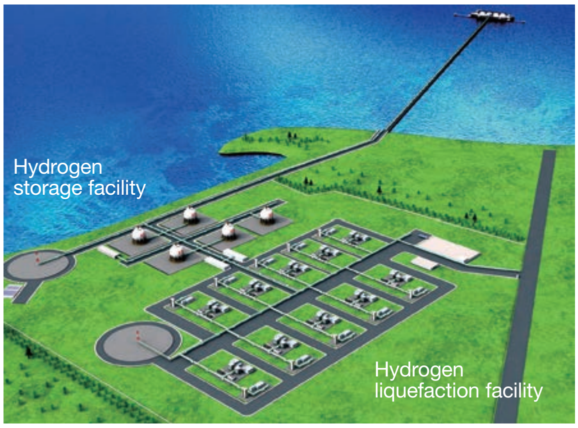
In order to evaluate the basic feasibility of this concept, we conducted conceptual design based on commercialization with the specifications shown in **Table 1** and the core facilities shown in **Fig. 3**, and evaluated economic efficiency by estimating the cost of equipment and

Table 1 Specifications of the CO_2-free Hydrogen Energy Supply Chain

Brown-coal consumption 〔Mton/year〕		4. 74
Hydrogen production	Oil equivalent 〔Mtoe/year〕	0. 764
	Volume 〔GNm³/year〕	2. 51
	Weight 〔ton/year〕	225, 500
CO_2 storage 〔Mton/year〕		4. 39
Liquefied hydrogen carrier		Two 160, 000 m³ carriers



(a) Hydrogen production site



(b) Hydrogen liquefaction/loading site

(c) Liquefied hydrogen carrier (160,000 m³ capacity)

Fig. 3 Core facilities of CO_2-free Hydrogen Energy Supply Chains

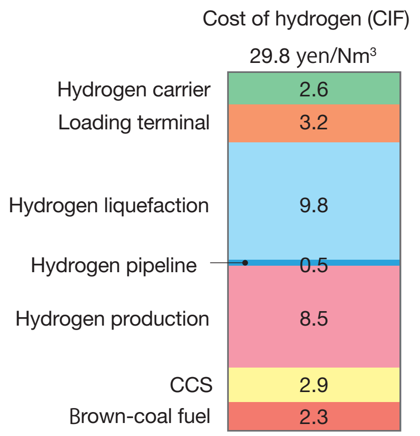


Fig. 4 Cost structure of CO_2-free hydrogen

operation. The commercialized hydrogen supply is equivalent to the amount consumed by three million fuel cell vehicles or a single one-million-kilowatt hydrogen gas turbine combined cycle power plant. As shown in **Fig. 4**, the Cost Insurance and Freight (CIF) for delivery to Japan was estimated to be approximately 30 yen/Nm^3 (334 yen/kg), of which the costs of raw brown-coal and CCS account for approximately 17%.

The CO_2-free Hydrogen Chains concept has the following features:

- Stable, large volume supply: hydrogen production from unused resources
- Good for the environment: on-site capturing and storing of CO_2 byproduct
- Enhance industrial competitiveness: technological and industrial ability sufficient for handling hydrogen required
- Restrain outflow of national wealth: does not result in just purchasing expensive resources

As you can see from the above, CO_2-free hydrogen meets the conditions required for future energy, that is, energy security, economic efficiency, environment and safety (3E+S).

This economic efficiency evaluation was conducted as an international project of the New Energy and Industrial Technology Development Organization (NEDO) and the outcomes have been recognized by both the Australian and Japanese governments.

3 Kawasaki's development of core technologies and products

In order to realize CO_2-free Hydrogen Chains, we need to make it "ready-to-use." The core technologies and products to produce, transport, store, and utilize hydrogen must be available to seamlessly operate from the beginning to the end of the supply chain. If even a single core product is missing, the supply chain will be interrupted and we will not be able to say we have put hydrogen into practical use. In addition, if a foreign product is needed anywhere in the supply chain, extra efforts and cost will be required to conform to standards and specifications.

"Ready-to-use" means the state in which not only the necessary technologies and products exist but also the rules and regulations required for operation and safety have been established. This is why technology development and rule establishment must proceed at the same time to realize the world's first CO_2-free Hydrogen Chain. Additionally, we must acquire intellectual properties at the same time to do business from an advantageous position. Therefore, we have been collaborating with stakeholders to work on technology development and the establishment of rules and standards for a liquefied hydrogen carrier, a loading arm for liquefied hydrogen, and so on.

One of our strengths in realizing a hydrogen energy supply chain is our technologies related to cryogenic liquefied gas that we have cultivated for many years, such as LNG carriers and the liquefied hydrogen storage tank and supply facilities at the Tanegashima Space Center. There are many different ways to carry hydrogen such as liquefied hydrogen and putting it in tanks, compressing hydrogen and putting it in gas canisters, and using absorbing alloys or organic compound media, but among them, liquefied hydrogen is already at the level of commercialization and is suitable for large-volume transportation and storage, and, it does not need any energy to convert it into ready-to-use hydrogen gas. Liquefied hydrogen is 70.8 kg/m^3 in density, lower than the 443 kg/m^3 of LNG, but has high volumetric efficiency. Specifically, it is approximately 800 times higher than atmospheric-pressure hydrogen gas. Also, it has a boiling point of 20.3 K, approximately 90 K lower than the 112 K of LNG, and low latent heat per volume, which requires high-efficiency liquefaction technology and high-performance insulation technology.

Major advantages of liquefied hydrogen are as follows:

- Already in practical use as transport media for industrial use and rocket fuel
- Highly efficient transport because no additional weight needs to be transported as it is not absorbed into or combined with any transport media such as metals and organic solvents
- Able to be evaporated at normal temperature on-site (energy is not needed)
- Once gasified, it is able to be supplied to a fuel cell without having to be refined, due to its high purity
- Able to be liquefied using less-expensive local energy when the supply site is located in an energy rich foreign country
- Able to contribute to cold energy power generation and

other purposes on-site by using the cold energy produced, because the energy when liquefied is not lost but converted into cold energy (-253°C)
- Clean and sustainable as it is non-toxic and has zero global warming potential (GWP)

We have been developing hydrogen technologies and products for its production, liquefaction, transportation, storage, and utilization, while advancing our cryogenic technology.

4 Progress of the project

To implement hydrogen energy in our society, all the core technologies from the supply side to the demand side should be seamlessly developed and linked, just like LNG. We have thus been engaged in hydrogen supply from overseas as part of the Japan-Australia pilot demonstration projects and in hydrogen utilization as part of the hydrogen gas turbine cogeneration demonstration project.

(1) Japan-Australia pilot demonstration projects

Toward the implementation of hydrogen energy in our society, we started conducting hydrogen energy supply chain technology demonstrations (Japan-Australia pilot demonstration projects) on a pilot scale (approximately 1/120 of commercial scale by carrier capacity) in fiscal 2020, including the world's first long-distance large-volume marine transportation of liquefied hydrogen produced from brown-coal-derived hydrogen. As shown in **Fig. 5**, this pilot project covers the whole hydrogen energy supply chain from the brown-coal gasification and hydrogen refining facility in Latrobe Valley through to the liquefied hydrogen unloading terminal at Kobe Airport Island, and will identify issues in technology, safety, operation, and social acceptance. It consists of the NEDO portion, which is a NEDO grant project called the Demonstration Project for Establishment of Mass Hydrogen Marine Transportation Supply Chain Derived from Unused Brown Coal, and the Australian portion, which is a grant project by Australian federal and Victorian state governments.

The NEDO portion is being conducted under the initiative of the CO_2-free Hydrogen Energy Supply-chain Technology Research Association (HySTRA), which was established in 2016 and is headed by us. The HySTRA's members are: Kawasaki Heavy Industries, Ltd., Iwatani Corporation, Electric Power Development Co., Ltd. (J-POWER), Shell Japan Ltd., Marubeni Corporation, ENEOS Corporation, and Kawasaki Kisen Kaisha, Ltd.

The Australian portion is conducted where Hydrogen Engineering Australia Pty Ltd (HEA), Kawasaki's subsidiary, serves as the main contact to the Australian governments. The participants are: Kawasaki, Iwatani, J-POWER and its subsidiary J-Power Latrobe Valley Pty Ltd (JPLV), Marubeni, AGL Loy Yang Pty Ltd, and Sumitomo Corporation.

In Japan-Australia pilot demonstration projects, Kawasaki is responsible for project coordination and the development and supply of technologies and device systems in each process.

(i) Gasification and gas refining

Figure 6 shows the brown-coal gasification and hydrogen refining facility. We delivered the following to JPLV: a preprocess facility to dehumidify and pulverize brown-coal to prepare it to be sent to a gasifier, and a facility to compress refined gaseous hydrogen and load it into land transport container trailers for delivery.

(ii) Liquefaction of hydrogen and loading of liquefied hydrogen

A site to liquefy high-pressure gaseous hydrogen has been constructed at the Port of Hastings. The liquefied hydrogen is loaded into container trailers made by Kawasaki, carried to the pier, and then loaded into a liquefied hydrogen carrier. **Figure 7** shows the hydrogen liquefaction terminal.

(iii) Liquefied hydrogen carrier

As a liquefied hydrogen carrier had never been built

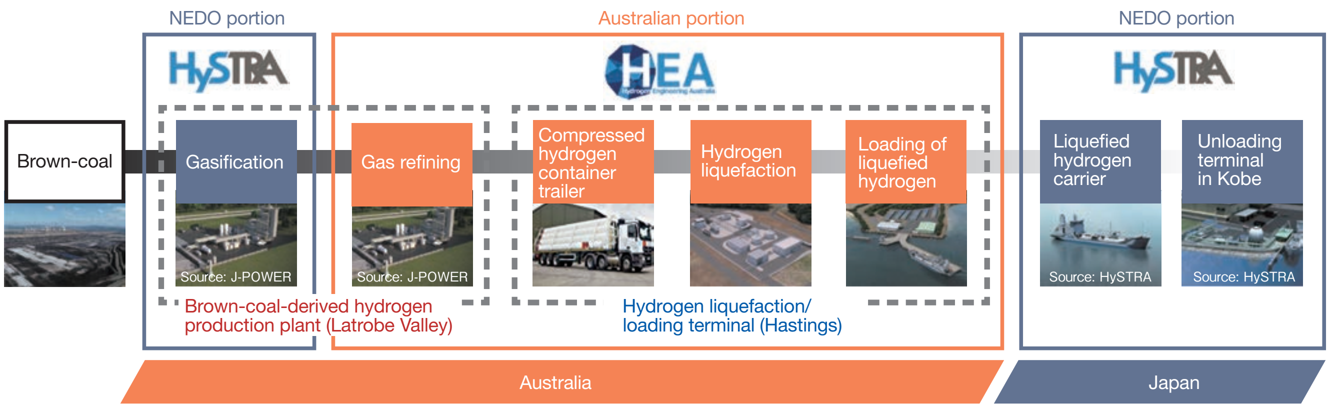


Fig. 5 The whole structure of Japan-Australia pilot demonstration projects

Fig. 6 Brown-coal gasification and hydrogen refining facility (February 2020)

Fig. 7 Hydrogen liquefaction terminal at the Port of Hastings

anywhere in the world, we designed one based on the IGC Code of the International Maritime Organization (IMO), namely, the International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk, which applies to LNG ships.

At the end of 2013, approval, in principle, was provided from Class NK for the cargo containment system installed in the liquefied hydrogen carrier (pilot demonstration carrier) for the Japan-Australia pilot demonstration projects. To get this approval, we proposed requirements for hull, materials, safety standards, and so on, taking account of the properties of liquefied hydrogen, as well as IGC code. Also, we conducted risk assessment by HAZID analysis.

To operate this liquefied hydrogen carrier, maritime authorities of Japan and Australia started discussions on safety standards in 2014, and the IMO approved interim recommendations for carriage of liquefied hydrogen in bulk in November 2016, which were a joint proposal by the two countries [6]. This became a steady step toward the realization of large-volume marine transportation of liquefied hydrogen.

The pilot demonstration carrier has a vacuum insulated storage tank (1,250 m^3 in capacity) with a pressure-accumulation cylinder structure, which can store boil-off gas internally, like a coastal LNG carrier. After the basic design was completed in fiscal 2016, then detail design was conducted and construction began. The naming and launching ceremony took place at Kobe Works in December 2019. The storage tank was installed into the carrier in March 2020, it was outfit as shown in **Fig. 8**, and the operation started in the fall of 2020.

(iv) Kobe unloading terminal

Constructing and operating a liquefied hydrogen loading/unloading terminal for bulk carriers will also be a

Fig. 8 Liquefied hydrogen carrier under outfitting (May 2020)

world's first, just like the liquefied hydrogen carrier. We are constructing an unloading terminal in an approximately 100 ha area rented from Kobe City in the northeast part of Kobe Airport Island. **Figure 9** shows how the terminal.

The onshore liquefied hydrogen storage tank has a 2,500 m^3 capacity, which is the largest in Japan. The world's first loading arm system (LAS) for liquefied hydrogen adopts the method of suspending a stainless-steel double-wall vacuum flexible hose from a trellis frame. The tip of the LAS is equipped with an emergency release system to safely block liquefied hydrogen leaks when a carrier leaves the port in an emergency.

The terminal construction was completed in May 2020, and after some test runs, full operation of the terminal started in the fall of 2020.

(2) Hydrogen gas turbine cogeneration demonstration project

We conducted technology development and demonstration of a new energy management system (EMS) on Port Island in Kobe City, which aims to efficiently use electricity, heat and hydrogen energy on a community level by using a heat and electricity supply system (hydrogen cogeneration system) which has a 1 MW-class gas turbine fueled by hydrogen and natural gas at its core. Obayashi Corporation served as the project organizer of the NEDO grant project, called the Smart Community Technology Development Project Utilizing Hydrogen Cogeneration Systems, and installed and operated an integrated EMS and a heat supply system, and Kawasaki delivered a hydrogen cogeneration system. This was a joint project by Kobe City, the Kansai Electric Power Co., Inc., Iwatani Corporation, Kanden Energy Solution Co., Inc., and Osaka University.

One of the pieces of equipment used in this technology demonstration is shown in **Fig. 10**. The facility is installed in an urban area, and it supplied heat and electricity to neighboring public facilities, namely, an international exhibition hall, a sports center, a central city hospital, and a sewage treatment plant. The operation of a 100% hydrogen-fueled gas turbine cogeneration system installed in a city area was a first-ever attempt in the world, and

Fig. 9 Liquefied hydrogen unloading terminal on the Kobe Airport Island

Fig. 10 Cogeneration facility with flexibility in the fuel mixing ratio of hydrogen to natural gas

Kawasaki's demonstration on April 19 and 20, 2018 was a complete success. The cogeneration system can change the fuel mixture ratio of hydrogen and natural gas within five minutes while it is running, and has the same properties, including generating-end efficiency, as the same system Kawasaki manufactures for natural gas applications.

5 Toward commercial operation

Japan-Australia pilot demonstration projects are approximately 1/120 of commercial scale by capacity of the liquefied hydrogen carrier. Therefore, after the pilot project, we must incorporate the outcomes and scale up various technologies, equipment, and systems toward commercial operation.

Since July 2019, Kawasaki has been working on scaling-up development of equipment and systems for a liquefied hydrogen energy supply chain toward commercialization in cooperation with Tokyo Boeki Engineering Ltd., Ebara Corporation, IHI Rotating Machinery Engineering Co., Ltd., and others, and we aim to complete such technology development by the end of fiscal 2022.

Conclusion

As hydrogen energy contributes not only to decarbonization but to energy security, economy, and job creation, many countries are launching demonstration projects. In step with Japan's policies leading the movement, Kawasaki has been striving to develop and demonstrate the technologies ahead of others, and is steadily making progress. As our next step, we would like to make use of our efforts to conduct businesses that realize a hydrogen economy, which some are saying will arrive earlier than expected.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We would like to express our deep gratitude to stakeholders for offering their great cooperation with our projects, and to supervisory authorities and local governments for subsidizing and supporting our projects and establishing relevant rules.

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