Chapter

Perspective Chapter: The Japanese Coal Mining Industry Reconsidered: From Mechanized Longwall Mining to Carbon Dioxide Capture and Storage

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Abstract

This chapter investigates the role of the Japanese coal mining industry in global coal mining development. In the twenty-first century, the Japanese coal mining industry was a marginal contributor to global production, with an annual domestic production of only 750,000 tons. However, as explained below, Japan has contributed to clean coal technologies and coal mining. The combination of chock shields and a double-ended ranging drum shearer is one of the major mechanized longwall mining systems worldwide. It was developed by the Taiheiyo Coal Mining Company in Japan in the mid-1960s and subsequently spread among major coal-producing countries. Japanese coal production systems and clean coal technologies have been transferred to Asian countries since the late-1980s. Currently, carbon dioxide capture and storage system in a mine under the seabed is being implemented by the Kushiro Coal Mine Company which succeeded the mine of Taiheiyo. In addition, Japan has developed technologies for coal-fired power plants to burn coal more efficiently and contains the world's most efficient ultra-supercritical coal-fired power plants. Furthermore, the world's largest Integrated Coal Gasification Combined Cycle power plants started operating to reconstruct Fukushima and reduce carbon emissions.

Keywords: Japanese coal mining industry, longwall system, technology transfer, coal gasification combined cycle, carbon dioxide capture and storage

1. Introduction

This chapter clarifies the role of the Japanese coal mining industry in the global development of coal mining in terms of technology and economic history. In addition, it investigates the role of Japanese technologies in utilizing coal in the trend of global decarbonization.

According to the International Energy Agency (IEA), the total amount of coal consumption in 2024 will increase by 0.3% compared to 2021, driven by increased coal consumption in China, India, Southeast Asia, Russia, and Africa, although developed countries such as G7 are tackling the issue of decarbonization [1]. However, decarbonized ironmaking technologies such as hydrogen ironmaking have not yet been operated commercially [1]. The supply of Liquefied Natural Gas from Russia became unstable following Russia's invasion of Ukraine. Therefore, the amount of global coal consumption will possibly increase more in the near-to medium-term.

In particular, the IEA estimates that the amount of coal consumption in the Asia Pacific will increase by 1.7% and account for 80% of global coal consumption, while Japan's coal consumption will decrease by 3.6% in 2024 compared to 2021. Coal production in China, India, and Indonesia accounts for 70% of global production. Including Australia, this increases to 75% of the global production [1], making the Asia-Pacific region the world's largest producer and consumer of coal.

In China, the world's largest coal-producing country, 87% of the total coal production comes from underground mines [2]. In contrast, open-cut coal mines are dominant in India, Indonesia, and Australia [1, 3]. However, coal mines have started mining underground in these countries because of a decrease in the amount of surface coal reserves, an increase in the amount of stripped soil, and various regulations for protecting the natural environment [3]. As a forerunner from open-cut mining to underground mining, the Vietnamese coal mining industry produces 73% of its coal from underground mines and will close all open-cut mines by 2030 [4]. The coal mining industry in the Asia-Pacific region has an increasing need for underground mining.

The Japanese coal mining industry produced a mere 60 million tons per annum, even in its flourishing period, which quickly declined after the late 1960s. Despite this, there exists a relationship between the above-mentioned situation in the global coal market and the Japanese coal mining/consuming industry. The global standard method of longwall mining, the combination of a double-ended ranging drum shearer (hereafter shearer) with chock shields, is based on the "Shield support and Drum shearer (SD) system" established by Japan's Taiheiyo Coalmining Company (Taiheiyo) in Kushiro City, Hokkaido, in the 1960s–1970s. Taiheiyo was a pioneer in longwall mining mechanization. At present, Kushiro Coal Mine Company (KCM) is part of a technology transfer project by the Japanese government.[1] Engineers who operated the SD system at Taiheiyo's colliery transferred knowledge on longwall mining and mine safety to other Asian countries, such as China, Vietnam, and Indonesia.

Japan imports more than 100 million tons of coal per annum and is the world's third largest coal importer after China and India. The Japanese electric power industry and heavy electrical machinery manufacturers have developed coal-fired power-generating technologies, introducing larger power-generating capacity, increasing thermal efficiency, and research and development of Integrated Gasification Combined Cycle (IGCC) power generation. Currently, the Japanese electric power industry operates many ultra-supercritical (USC) coal-fired power plants that have the world's highest gross thermal efficiency. These coal-fired power plant technologies are also exported to Asian countries to reduce carbon emissions, although it is becoming difficult to export these technologies due to the expansion of decarbonization in the world.

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[1] Taiheiyo stopped operating mines in 2002. Thereafter, KCM was established to inherit the operation of the mine staked by the local businesses in Kushiro City.

Former Prime Minister Yoshihide Suga declared the goal of "2050 Carbon Neutrality," which demonstrated that the Japanese government will aim to decarbonize the economy in step with G7 countries. However, this does not mean that Japan has to abandon the technologies for coal mining and utilization that it has accumulated. It is an important duty of Japan, one of the world's largest coal consumers, to correctly record the experience of developing coal-related technologies and transfer them to countries that need them as it takes a long time to achieve energy transition [5].

Many studies have focused on the Japanese coal mining industry after the Second World War, including policy studies of industrial policies for rationalizing the coal mining industry [6, 7] and historical studies of workers and their communities [8–11]. These studies clarified the process of industrial decline by focusing on the government, companies, workers, unions, and communities. However, research on coal-related technologies from the perspective of social science has only recently begun [12–15]. This chapter contributes to improving the understanding of coal-related technologies in Japan.

2. Brief history of the Japanese Coal Mining Industry

According to an investigation in 2008, Japan's proven and recoverable coal reserves stand at 4.8 billion tons and 352 million tons, respectively [16]. The most unique characteristic of coal reserves is the existence of subsea coalfields, which comprise 18% of the total coal reserves. Annual production from reserves has been almost 100% of the total production since the late 1990s, while the corresponding number was 12% in 1958 [17, 18]. This indicates that production from subsea coalfields is essential for the Japanese coal mining industry.

As shown in **Figure 1**, the modern Japanese coal mining industry started to develop in the late 19th century and declined after 1961, when it produced approximately 55

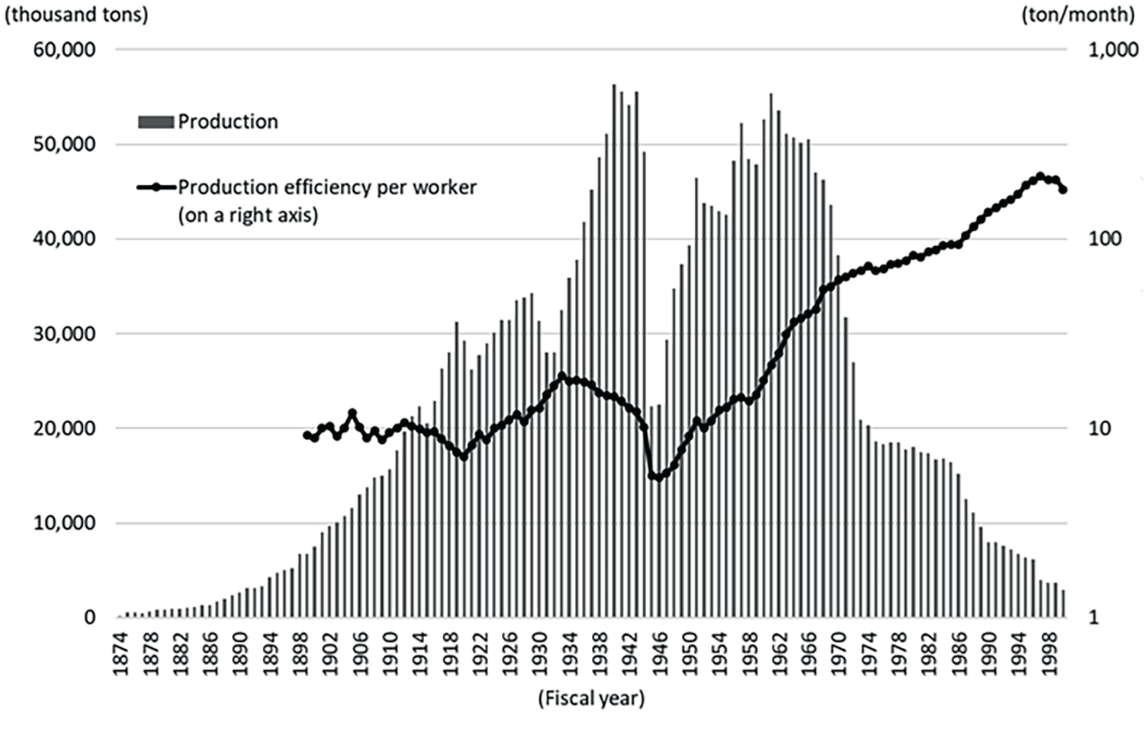

Figure 1.
Coal production and production efficiency in Japan, 1874–2000. Source: [18].

million tons. Today, some coal mines produce a mere 750,000 tons per annum in 2020 [19]. On the other hand, production efficiency increased rapidly despite the decline in industry. The monthly production efficiency per worker was 200 tons in the 1990s, compared to only 5 tons in the late 1940s. This indicates the rapid mechanization of production as well as a rapid decrease in the number of workers.

The Japanese government launched a set of policies for the rationalization of the coal mining industry in 1963 to deal with the industry's decline caused by the energy revolution. Financial support measures, such as concessional loans, subsidies, and leases of machinery, were implemented to promote investment by coal companies in facilities and machinery. This financial support was provided by the government, the most notable of which was the import petroleum tariff after 1967. Financial support from the government continued until FY 2001, when the total amount reached staggering proportions [18]. For example, concessional loans alone amounted to approximately 330 billion yen, that is, approximately $2.4 billion.

Furthermore, Sekitan Gijutsu Kenkyuusho (Coal Mining Research Center) was established in 1960 through joint investment by the government and coal companies. Engineers from both coal and machinery companies collaborated for experiments and research projects to enable innovation in coal production technologies [15]. Thus, the coal mining industry has created institutional and financial support to spur technological innovation.

However, the coal mining industry has been forced to introduce basic technologies from abroad. Mining engineers not only collected mining journals from Europe and the United States but also sent overseas inspection groups to study advanced coal production technologies [20]. In addition, mining engineers have studied the coal production technologies of the USSR because many Japanese coal mines excavated coal using inclined shafts, such as used in mines in the USSR, in contrast to the vertical shafts in continental Europe [21]. Following these experiences, various types of mining machinery were imported. Thus, the coal mining industry promoted the mechanization of coal excavation. One of the most notable successful examples is the mechanization of longwall mining, which Taiheiyo developed as the "SD system" in the late 1960s. Taiheiyo operated a subsea mine in Hokkaido, on the northern island of Japan. In the next section, we will investigate Taiheiyo's technological development history.

3. Struggle to mechanize longwall mining: Development of the SD system

In the 1960s, Taiheiyo made an effort toward the practical application of powered support. In May 1960, Ferromatik rotating powered supports, which were frame-type powered supports, were introduced as Taiheiyo's first powered support. However, because of the small contact area of the base of the powered support, insufficient thrust of the shifter, insufficient strength of each member, and other factors, Taiheiyo was unable to obtain the desired results [22]. Next, the company introduced an IU-shaped, frame-type, six-leg powered support (MKSP-LIU model, FIU model) manufactured by Mitsui Miike Machinery (Miike Machinery). A low seam with a coal height of approximately 1 meter was selected for the machine to conduct operations. The coal-cutting machine adopted a tandem-type coal plow, where the machine height changed according to the height of the coal face, and the machine began full-scale operation in October 1963 [23]. This low-seam mining achieved good coal output after partial improvement of the IU frame (from the LIU model to the FIU model) [24]. However, many occupational accidents occurred because of the narrow space of the low seam [25].

In parallel with low-seam mining, Taiheiyo aimed for the practical use of powered supports in thick seams. When designing the powered support, it is necessary to estimate the amount of roof lowering when using the powered support and determine the stroke amount required for the hydraulic prop to avoid the complete retraction of the powered support on the coal face. Therefore, experiments that simulated repeated lowering and sequential lowering, which are shoring movements unique to powered support, were conducted using hydraulic props and link bars, and the roof subsidence behavior when using the powered support was clarified from the measurement results [26, 27]. Based on their findings, a UU-shaped, frame-type, 12-leg powered support (MKSP-FUU model) was developed by Miike Machinery, which had two hydraulic props in the rear row. UU frames (UU) were introduced for simultaneous multi-pass longwall mining in combination with a coal plow and underground tests began in May 1964. Various modifications, such as changes to the method for connecting the hydraulic prop and base and the shortening of the base length, were made to the UU based on the findings obtained through the tests [28–30].

In February 1965, Numajiri No. 2 Longwall began operations using the improved UU. However, the expected efficiency improvements were not achieved. In the UU, hydraulic props with corresponding relationships were connected to each other at the front, back, left, and right. This resulted in the frequent occurrence of frame inclining owing to the relative horizontal movement of the roof and floor, as well as hydraulic prop damage owing to eccentric loading. Additionally, there were many structural problems, such as the need to correct the direction of the powered support, forepoling, and inflow of rock debris from the gob area. As a result, mechanized mining of this thick seam failed [22, 31, 32]. In the section where an attempt was made at the practical application of UU, from the second half of 1965, the lower-seam longwall for simultaneous multi-pass longwall mining was switched from UU frames to single hydraulic props and link bars.

Efforts toward the practical application of powered support continued and surplus UU frames that were lifted to the surface were dismantled. After dismantling, the materials were used to develop an in-house THY chock support, which is a chock-type powered support that is connected to a conveyor. THY chocks were tested in combination with UU frames. The linearity of the powered support was improved by adopting a conveyor connection. Additionally, to improve frame inclining, an adjusting jack was made and installed using scrap material from a single hydraulic prop and a simple shield plate was made and attached to prevent the inflow of rock debris from the roof and gob area [31, 32].

However, damage to the hydraulic prop owing to the horizontal force of the coal face roof was structurally unavoidable with the frame-type powered support and chock support. At that time, the only powered support with a structure that could withstand horizontal forces was the OMKT shield support (OMKT) developed in the USSR. As shown in **Figure 2**, the OMKT was a type of powered support called a shield support, which was covered with steel plates on the top and rear. The OMKT used a pin-hinge structure to hold both ends of the hydraulic prop and no horizontal force or bending moment was applied to the hydraulic prop. In December 1965, Miike Machinery formed a technical collaboration with the USSR's export corporation for the OMKT and began preparations for licensed production [33]. Taiheiyo received 20 sets from Miike Machinery for trial use [32].

In addition, a shearer was adopted for the coal-cutting machine combined with the OMKT. Equipping both sides of the machine body with ranging arms with

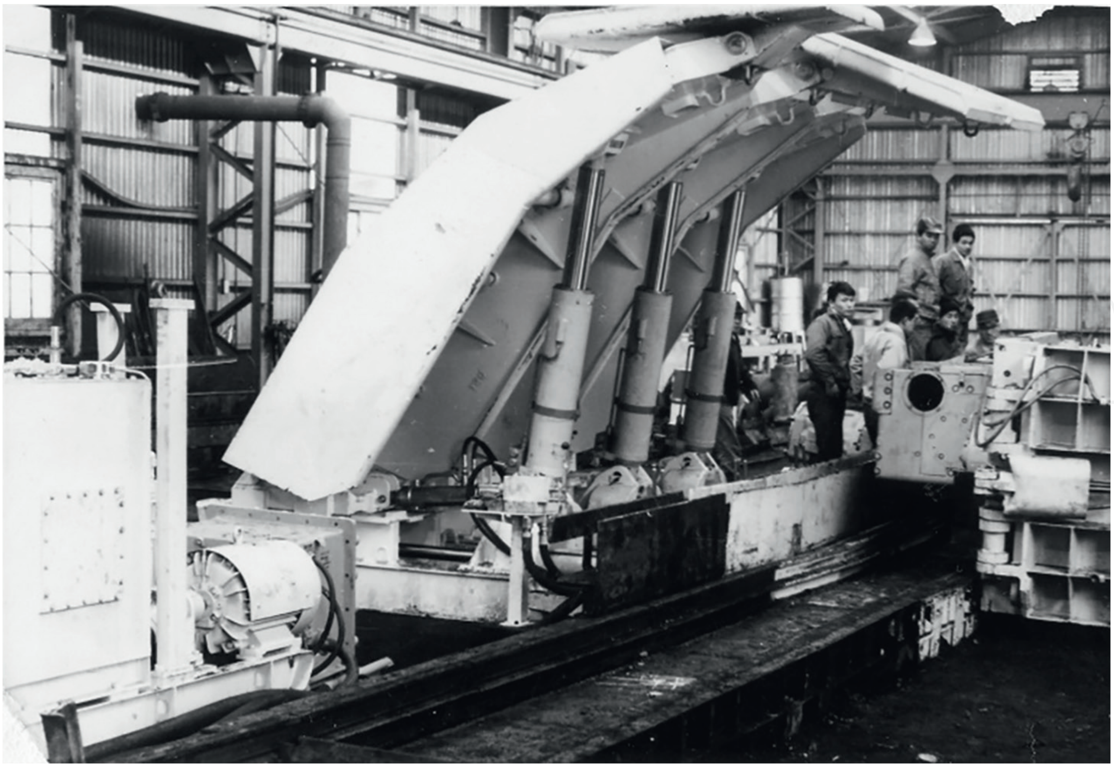

Figure 2.
The OMKT shield support. Source: This figure is owned by the Kushiro Board of Education, Hokkaido, Japan.

cutting drums made it possible to cut both ends of the coal face. The double-ended ranging drum shearer was domestically produced by Miike Machinery in 1966 [34]. The MCLE200-DR8090 model manufactured by Miike Machinery was delivered to Taiheiyo. A coal planer with a modified coal plow that can load cut coal and cut the bottom wall was installed to supplement the cutting and loading by the shearer [35].

In addition to changing the cutting machine and powered support, the longwall coal mining method was fundamentally reconsidered. The length of the coal face was set extremely short at 35 meters to keep the load on the roof at the center of the coal face small. Furthermore, shortening the round-trip time of the shearer and accelerating the progress of the coal face enabled the advancement of the powered support before the deterioration of the roof, and it was thought that the complete retraction of the powered support could be prevented [35].

To handle this rapid progress, the stable was abolished because of the difficulty of mechanizing it and the requirement of manual labor. First, the drive unit, which was conventionally installed on both stables on the head-gate and tail-gate sides, was integrated into the head-gate side, and the stable on the tail-gate side was abolished. The return end of the armored face conveyor (AFC) on the tail-gate side and the sprocket of the coal planer were coaxial to avoid interference between the cutting drum and AFC, which allowed the drum to enter the end of tail-gate side and complete the cutting of the longwall. Next, all the drive parts on the head-gate side were pulled out to the head-gate. This was made possible by adopting a separator system at the entrance from the AFC to the head-gate conveyor. As a result, the stable on the head-gate side was also abolished and became a non-stable system. Additionally, a snaking panzer conveyor was developed to respond to the rapid relocation of facilities such as the head-gate conveyor. This conveyor was installed parallel to the normal straight panzer conveyor that was installed at the head-gate and, by overlapping the snaking tip, it became possible to shorten or lengthen the head-gate conveyor without interfering with the operation on the coal face [35]. These head-gate facilities later led to the development of the stage loader.

This coal mining method was called "SD system," which was an acronym for the main constituent machines: the shield support and drum shearer. In April 1967, the test coal face Higashi-Masuura Left No. 1 Level Rise No. 4 Longwall was set up and the first SD system began operation. Despite facing difficulties, such as mechanical failure and roof fall, the equipment was improved and the number of props built in the OMKT was increased from the original one to two to increase the supporting capacity. Progress was generally favorable after the introduction of the reinforced OMKT in Longwall no. 10 [35].

However, the OMKT, which was originally developed for shallow areas, could not overcome the lack of structural support. Therefore, Taiheiyo and Miike Machinery, learning from the OMKT-MK shield support, which had a lemniscate linkage at the connection between the caving shield and base, developed a new chock shield that had a long main canopy, four hydraulic props that supported it, and a lemniscate linkage at the connection between the base and the caving shield. The adoption of the lemniscate linkage enabled nearly vertical retraction of the entire canopy while maintaining a fixed distance between the canopy tip and faceline. This four-leg chock shield with a lemniscate linkage was called the "SMK chock shield support (SMK)" [33, 36] (see **Figure 3**).

In December 1968, 10 sets of SMK were introduced to Numajiri West No. 23 Level No. 1 Main-seam Longwall, along with single hydraulic props and link bars, and tests were conducted. In November 1969, operation began at the Minami-Masuura No. 3 Level No. 3 Longwall, where the SMKs were installed across the entire coal face [37]. The coal output was good after the introduction of SMK and the supporting capacity

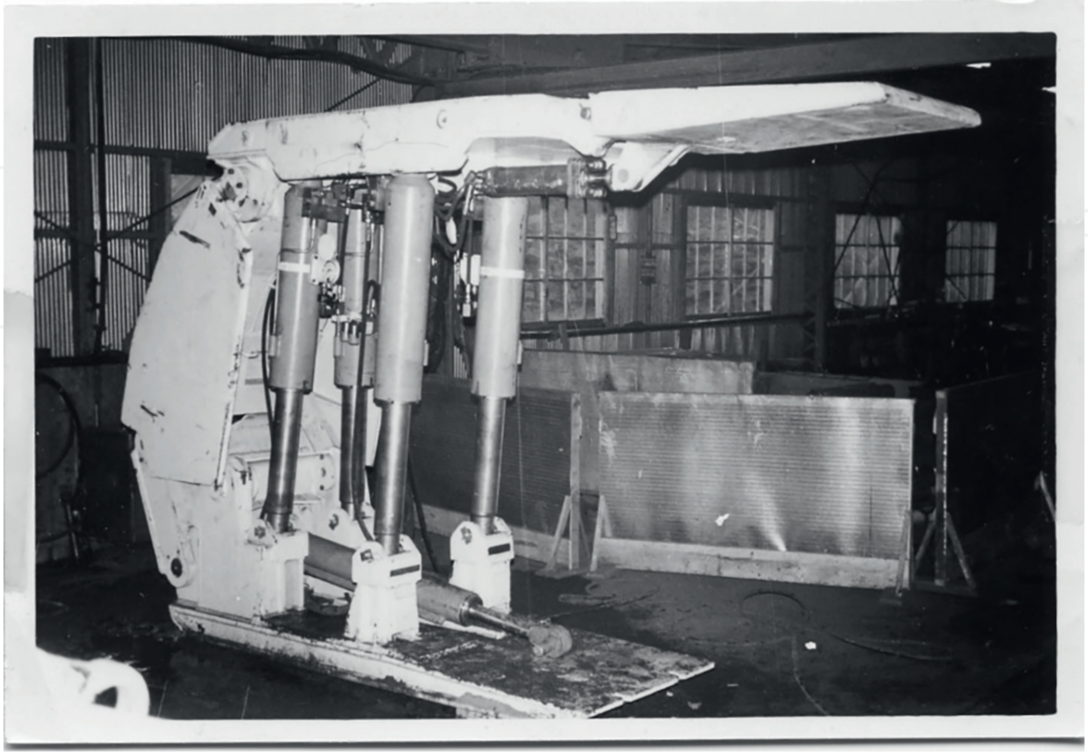

Figure 3.
The SMK chock shield support. Source: This figure is owned by the Kushiro Board of Education, Hokkaido, Japan.

of the powered support was completely resolved. The supporting capacity of the powered support increased from 80 tons for the first monopod-type OMKT to 160 tons for the reinforced OMKT. Following the development of SMK, improvements and strengthening were conducted as the length and depth of the coal face increased. The TY-2 model introduced in 1968 had a capacity of 320 tons, the TY-3 model introduced in 1971 had a capacity of 400 tons, and the NT-1 model introduced in 1988 had a capacity of 600 tons. The length of the coal face gradually expanded from 35 to 100 m in the 1970s, peaking at 250 meters in the 1990s [38, 39].

The four-leg chock shield with lemniscate linkage was a well-balanced powered support that could withstand the complex and difficult underground natural conditions of Japanese coal mines. The development of this four-leg chock shield with a lemniscate linkage was a breakthrough not only in Japan but also in coal mining technology worldwide. This technical information spread worldwide through a licensing agreement with the West German company Westfalia in 1971, published in the West German magazine *Glückauf* Vol. 109 No. 14, exports of the longwall system to Australia in 1975, and international sales by the manufacturer Miike Machinery [32, 33]. It can be said that today's standard longwall system was established through this series of technological developments. This establishment not only brought about a dramatic improvement in coal production efficiency but also made it possible to protect miners from the inflow of rock debris from the gob area and roof falls, which contributed to occupational safety.

4. Overseas transfer of coal production technologies

4.1 Export of SD system and related technologies

4.1.1 Exports of SD system to Australia and other countries

In 1975, the SD system developed in Taiheiyo was exported to the South Bulli Coal Mine (South Bulli) of the Bellambi Coal Company in Australia. The powered support that constituted the longwall system was a four-leg chock shield with a lemniscate linkage made by Miike Machinery, with a yield load of 480 tons and support width of 1.25 m. A DR8394 model manufactured by Miike Machinery, which had a motor output of 300 kW, was adopted for the double-ended ranging drum shearer [34].

The South Bulli mine introduced British and West German chock supports since it began longwall mining in the mid-1960s but both failed because of the lack of support. The roof of the 2.4–2.7-m height Bulli seam, which is the main coal seam for operation in the mine, is Coal Cliff Sandstone, which is a superhard rock, and it is difficult to handle the roof pressure derived from it. In April 1973, Taiheiyo was asked to consider adopting an SD system to break this deadlock and a letter of intent was issued in March 1974. Taiheiyo Kouhatsu, a parent company of Taiheiyo, then established Taiheiyo Engineering Inc. (TEI) in July 1973 to establish an export system.

The supporting capacity of the powered support was given the highest priority when designing the longwall system. The measurement results communicated by the chief engineer at Bellambi indicated a necessary meter run for the face of 320 tons/m for the Bulli seam and a powered support with a yield load of 480 tons was designed based on this result. It was determined that the load capacity of each hydraulic prop must be increased to 120 tons to meet the performance requirements. Sumitomo Metal Industries developed a new large-diameter drawn steel pipe to satisfy these requirements.

Following test chock shield load tests at a research institute for coal mining in West Germany in November 1974, the entire system was tested outside the mine in June 1975, with operations beginning at the coal mining site in October 1975. When operations began, there were problems with the operation of the machine owing to the large frictional resistance caused by the weight of the shearer, as well as problems with the operation of the coal planer for loading coal. Improvements were made through on-site creativity and the issues were resolved. Importantly, the supporting capacity of the powered support, which could have fatal consequences in the event of a defect, withstood the first weighting of the starting section and functioned as designed. This was revolutionary because it succeeded in designing a longwall system based on measurements and knowledge from mining theory. The success of longwall mining also contributed to company management. Sydney Morning Herald reported that the net profit for the first half of 1976–1977 was 447% of that of the previous period. Subsequently, the longwall system continued to be used without any maintenance outside the mine until its planned end in 1986 [32, 34].

As shown in **Table 1**, the SD system and shearers produced in Japan were exported to other parts of Asia, Australia, and the United States [34, 40]. Less than 10 years after the SD system was introduced in Japan, it became a global standard for longwall mining. However, machinery manufacturers in Europe and the United States started increasing exports of longwall systems similar to the SD system after the 1980s because they succeeded in producing a power support akin to the Japanese design [34].

4.1.2 Participation in the project led by the United States Bureau of Mines

The TEI also participated in a project by the United States Bureau of Mines (USBM). In 1974, the USBM put out a public offering for a new technology for mining the thick seams found in the western United States to replace the widely used room coal mining in the United States. Consolidation Coal, Foster–Miller, and TEI were jointly awarded the order. Foster–Miller approached the TEI in the summer of 1974 and joined the project. The outline of the proposal was to conduct non-simultaneous multi-slice mining in advance of the upper layer based on the SD system developed by Taiheiyo.

Year	Destination	Unit
1975	Australia	1 set of longwall system and 1 shearer
1978–1979	China	1 set of longwall system
1980–?	North Korea	3 sets of longwall system
1982	Australia	1 set of longwall system
1985	Australia	1 shearer
1985–?	United States	9 shearers
1986	Australia	2 shearers
1991	Australia	1 set of longwall system

Notes: This table shows only the export products produced by Miike machinery from the 1970s to the 1990s.

Table 1.
Exports of the SD system and shearers from Japan. Source: [34, 41].

The measurement and analysis results of various rock behaviors accumulated at Taiheiyo's colliery were used as mining evidence for this proposal. First, the surface subsidence mechanism caused by the breaking of the upper rock strata and compression of fallen rock debris in the gob area during thick-seam mining was clarified based on actual measurement data on the changes over time in surface subsidence in the cases of single-seam mining and multi-seam mining at Taiheiyo's colliery. Additionally, the solidification state of fallen rock debris in the gob area of the upper layer, which becomes an artificial roof when mining the lower layer in multi-slice mining, was clarified from actual measurement data on the rock solidification of the main seam at Taiheiyo's colliery. Its low porosity indicated that it could be handled by chock shields. Furthermore, the mechanical and technical evidence included references to the practical application process for powered support at Taiheiyo's colliery, with the experience from use in the field and the improvement process shown by the introduction of the frame-type powered support made by Miike Machinery (i.e., UU frame) to the in-house developed chock support (i.e., THY chock support), OMKT, and four-leg chock shield with a lemniscate linkage.

This mining and practical knowledge were highly regarded and led to the order of this project. In April 1975, a proposal entitled "the Technical Proposal for the Demonstration of a Thick Seam Mining System" was created and submitted to the USBM [32].

4.2 Technology transfer from Japan to Asian countries

The Japan Technical Co-operation Center for Coal Resources Development (JATEC), which was established by a joint investment by many coal mining companies to investigate and develop overseas coal resources in 1990, started receiving technical trainees from the Ombilin Coal Mine in Indonesia [42]. Simultaneously, the Ministry of International Trade and Industry (MITI) devised a project for mine safety improvement and increased production in the Asian coal mining industry through technology transfer from Japan. JATEC undertook the technical training program component of the project from MITI and was entrusted with implementing the program with coal mining companies, including Taiheiyo. After this project was successfully completed, a new and enlarged technology transfer project was implemented by the New Energy Development Organization (NEDO) in the late 1990s [13, 14]. Finally, in FY 2002, the Ministry of Economy, Trade and Industry (METI), that is former MITI, devised a five-year project, where NEDO maintained the operation of domestic coal mines and served as a technology transfer hub to Asian coal mining industries [18].[2] KCM was entrusted with the operation of the project from NEDO because it inherited the coal mine that Taiheiyo had stopped operating at the end of FY 2001.

As shown in **Table 2**, the technology transfer program included the reception of technical trainees and dispatch of mining engineers. Between FY 2002 and FY 2013, the program included 2735 technical trainees from Vietnam, China, and Indonesia, 3680 Japanese mining engineers, and 88,074 trainees who completed training in the three above-mentioned countries. In terms of the number of people involved, the program in Vietnam was the largest.

To demonstrate the program details, the case of KCM, which has implemented the program since FY 2002, will be outlined here. KCM received 367 trainees in five

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[2] After FY 2012, the Japan Oil, Gas and Metals National Corporation (JOGMEC) inherited the project from NEDO.

Recipient country	China	Vietnam	Indonesia	Total
Received trainee	953	1344	438	2735
Dispatched engineer	467	2553	1440	3680
Trainee at home	19,249	54,000	14,825	88,074

Unit: Person.
Notes: The reception of trainees from Indonesia was conducted from FY 2002 to FY 2009. The number of dispatched engineers and trainees at home is not the actual count but the total count.

Table 2.
Results of the coal technology transfer program, FY 2002–FY 2013. Source: [43, 44].

training courses spanning 10–24 weeks from FY 2002 to FY 2003. The curriculum was as follows: on-the-job underground work using mining machines, classroom lectures on the Japanese language and business management, and demonstrations on mining methods using a miniature model of a mine and computer technologies [12]. Mining engineers dispatched from the KCM conducted practical training and classroom lectures at overseas mines for 3 months. Although the transfer of production technologies was partial, the technology transfer project won high praise from recipient countries because of the successful transfer of knowledge on mine safety and mining operations [12].

In recipient countries, the technology transfer program contributed to the production rationalization of the coal mining industry; for example, an increase in production efficiency, a decrease in the occurrence rate of mine accidents, and heightened awareness of technology improvement and mine safety among ex-trainees [45]. Due to this, the technology transfer project continues to this day, despite originally being planned to last for 5 years.

KCM needs to continue implementing the technology transfer program because the program contract fee is one of its main sources of revenue [42]. If the project was abolished, the KCM could not continue operating its mines. This means that the Asian coal mining industry would lose the chance to learn about the production technologies that the Japanese coal mining industry has fostered over its history. As mentioned in Section 1, there is an urgent need for underground mine safety transfer because coal mines have increasingly started underground operation in Asian countries because of a decrease in the amount of surface coal reserves, increase in the amount of stripped soil, and various regulations for protecting the natural environment [3]. Therefore, the Japanese government and METI have to continue the technology transfer project to maintain KCM's operation and make Asian coal mines safer and more efficient.

5. Coal as clean energy: USC, IGCC, CCS, and Carbon Capture, Usage and Storage (CCUS)

5.1 Coal-fired power plants

As long as coal-fired power generation is still used in China and worldwide, improving its efficiency and applying clean coal technologies remains an urgent issue. Japan has accumulated technologies that can solve these problems in conventional coal-fired and IGCC power generation.

The late 1950s saw the start of the shift from coal to oil as the main energy source in Japan, or the energy revolution. During this period, the Japanese electric power industry promoted a power-supply approach that involved a shift from reliance on hydropower to thermal power. The electric power industry continued to use domestic coal based on government and coal industry requests, while increasing the number of heavy oil-fired power plants that used inexpensive Middle Eastern heavy oil as fuel. Meanwhile, the electric power industry, in cooperation with Mitsubishi Heavy Industries, Hitachi, IHI, and others, worked on domestic production and the improvement of imported technologies. By the late 1960s, the Tokyo Electric Power Company (TEPCO) started operating a 600-MW supercritical pressure power plant with a net efficiency of 40.3%, catching up with the plants in operation in Europe and the United States [46]. In the early 1980s, J-POWER began operating a 500-MW supercritical coal-fired power plant. Furthermore, in the 1990s, J-POWER successfully operated a 1000-MW USC coal-fired power plant. Currently, Japan's coal-fired power generation technology is at the highest level in terms of power generation efficiency worldwide, with the net efficiency of the country's most efficient power plants reaching 48%, which has contributed to reducing coal consumption and CO_2 emissions [47, 48].

Simultaneously, the scale of conventional coal-fired power generation has progressed and research and development into IGCC has also progressed. The description below is based on cited references and an interview with Yoshihiko Horie, Plant Chief Superintendent of Nakoso IGCC Power LLC, on 17 November 2022. IGCC is a technology that gasifies coal and generates electricity with a gas turbine and steam turbine that uses exhaust heat, with research and development beginning in Europe, the United States, and Japan in the 1970s. Japan's unique air-blown IGCC technology began in 2007 with a 250-MW demonstration unit at the Nakoso Power Plant of Joban Joint Thermal Power in Fukushima Prefecture. The demonstration unit was successful, achieving a high net efficiency of 42.9% and began commercial operation in 2013 [49].

In 2015, the Japanese government announced a policy aimed at accelerating recovery from the 2011 Great East Japan Earthquake and Fukushima Daiichi Nuclear Power Plant Accident. In response to this policy, TEPCO, Joban Joint Thermal Power, and the Mitsubishi Group roughly doubled the scale of the demonstration unit at Nakoso and launched the Fukushima Recovery Power Project to build and operate the world's largest and most efficient IGCC thermal power plant in Fukushima, establishing Nakoso IGCC Power LLC and Hirono IGCC Power LLC in 2016. In this chapter, the case of the Nakoso IGCC Power is discussed. The location selected for the new power plant in Nakoso was agricultural land that suffered salt damage due to the tsunami caused by the earthquake and the project created local employment for those affected. Engineers at Nakoso faced various technical problems that were associated with the scaling up of the unit but the engineers proceeded with work to begin power generation in 2020 while resolving these issues and started commercial operation in April 2021. As of 2022, the Nakoso IGCC power plant had an output of 525 MW and net efficiency of 48%, making it the world's largest and most efficient coal gasifier on a per unit basis.

IGCC is a power generation technology with a lower environmental impact than conventional coal-fired power generation methods. The first benefit is the reduction in greenhouse gas emissions. The CO_2 emissions of IGCC power plants are 15% lower than those of conventional coal-fired power plants. The second benefit is the expansion of the type of coal that can be used. Conventional coal-fired power generation uses coal with a high ash melting point, which is less likely to generate clinkers. In contrast, IGCC power generation can use coal with a low ash melting point. The third benefit is that coal ash becomes slag-like, which not only halves the volume needed but also allows the material to be reused as cement or pavement material.

In the 2020s, Japan's main coal supply sources were Australia and Indonesia, and conventional thermal power generation uses coal from these sources, whereas the Nakoso IGCC power plant uses American coal. Combining IGCC power generation with conventional coal-fired power generation enables the reduction of the environmental impact of coal combustion and efficient use of resources. The COVID-19 pandemic and the effects of "decarbonization" in developed countries have resulted in the stagnation of IGCC technology exports from Japan to overseas. However, since a stable supply off fossil energy is expected to become unstable, the value of IGCC technology should be revised upward. Additionally, NEDO, J-POWER, and Chugoku Electric Power Company have been conducting Integrated Coal Gasification Fuel Cell Combined Cycle demonstration tests by applying the IGCC technology (Osaki CoolGen Project) in Hiroshima in 2022 [50, 51].

Despite the decline in the domestic coal mining industry, one of the reasons for the advancement of coal-utilization technologies in Japan was the import of steam coal, which was promoted as a countermeasure to the soaring oil prices seen after the oil crisis. At the beginning of the 1970s, unlike the coking coal trade, where long-term contracts were the norm, the steam-coal trade commonly involved spot contracts and a large-scale global market based on long-term contracts had not yet formed. Under these circumstances, in 1974, Australia, which had previously banned the export of energy resources such as uranium, petroleum, and steam coal, lifted its ban on the export of steam coal [52]. This was achieved through negotiations between the Australian government and J-POWER, which was planning to build a large-capacity coal-fired power plant utilizing imported steam coal, and a summit meeting between the Japanese Prime Minister (Kakuei Tanaka) and Australian Prime Minister (Gough Whitlam) in November 1974 [53]. Subsequently, Japan increased its imports of steam coal, including from Australia, America, Canada, China, and Indonesia. Japan also contributed to the expansion and globalization of the steam-coal trade market.

5.2 Challenging coal production and utilization with CCUS at KCM

The description below is based on an interview with Hiroyuki Matsumoto, Senior Managing Director of KCM, on 22 March 2022. The KCM is working on a resource recycling project that integrates the operation of an underground coal mine and thermal power plant. This is based on the Kushiro Resources and Energy Ecopark Concept, which was formulated by the company in 2011. The concept was to organically link the company's coal production, training, and environment-related businesses and to establish a resource and energy-related research and education center, the core of which is the construction of a new thermal power plant. In Kushiro City, the local government also supported the power plant construction plan because it was informed that there was a risk in the surrounding area due to the uneven distribution of the power supply as a result of the absence of a core power plant.

The Kushiro thermal power plant, which started operation in 2020, has a small output of 112,000 kW and uses a circulating fluidized bed (CFB) boiler to conduct mixed combustion of Kushiro coal and overseas biomass. The biggest advantages of adopting a CFB boiler instead of pulverized coal firing are that there is no need for fuel pretreatment, the mixed combustion of biomass and waste is easy, and the fuel can be changed based on the circumstances.

Additionally, KCM has been entrusted with the operation of the Kushiro Wide-Area Federation Incineration Plant. It dispatched engineers and operators and has had a track record of the stable operation of a fluidized-bed gasification melting furnace and small-scale power generation plant there. On the other hand, the calories from coal and biomass are almost constant in the new power plant. Thus, boiler operation is less difficult than general waste incineration, which involves large calorie fluctuations. Having the manpower of experienced boiler operators was a stepping-stone in the thermal power generation plan.

A CFB boiler uses less cooling water than a pulverized coal-fired boiler. As a result, although a supply line from the water supply is secured, most of the aforementioned demand can be covered by the underground water of the coal mine. Furthermore, the thermal wastewater discharged from thermal power generation is returned to the coal mine and used as coal-preparation water. Even as a coal preparation plant, this has the advantage of preventing the freezing of the coal-preparation water in winter. Fly ash discharged from thermal power generation is also supplied to coal mines and is used as a filling material in underground mining pits.

In underground coal mines, the company changed its production system to achieve integrated operation with thermal power plants. Because the production scale was reduced from 500,000 tons per year to 300,000 tons per year for local production and consumption, the one-coal-face system of longwall mining was abolished and switched to the four-coal-face system of room and pillar mining. With the top priority of a stable supply of coal to local thermal power plants, the company shifted from a centralized production system to a risk-diversified production system. The company called this the New Coal Production System.

A unique method was adopted for room and pillar mining as part of a Resource Recycling Project. In normal room and pillar mining, mining is conducted in a grid pattern while leaving security coal pillars and mining traces are not filled. However, the room and pillar mining conducted by KCM differs from the usual mining method in that it extracts coal by digging branches into the coal bed and fully filling each branch with fly ash. As will be described later, technological development is being conducted to connect this full filling to Carbon Dioxide Capture and Storage and Carbon Capture, Usage and Storage (CCUS).

The KCM is actively conducting joint research with universities, academic societies, and companies. Although the number of underground mines in operation in Japan has decreased, the mine has served as a valuable research site for resource engineering, geology, and rock mechanics. For example, as part of a resource recycling project, KCM is working with the Osaka Gas Company to develop concentration technology for underground methane gas, which is used as fuel for its in-house boilers. Currently, joint research is being conducted on CCUS. This involves mixing carbon dioxide with fly ash, which is used as a filling material for room and pillar mining. This carbon dioxide reacts with the Ca and Mg in the fly ash and improves the strength of the filling material through carbonate mineralization. A demonstration test was conducted and favorable results were obtained. As this is currently in the demonstration test stage, carbon dioxide is externally procured; however, following the completion of the demonstration test, the company is looking to install carbon dioxide separation and capture equipment at the thermal power plant.

As shown above, KCM has been able to utilize its technological base and human resources to operate its underground coal mine and thermal power plant in an integrated manner and is positioned as a base for various research and development efforts. KCM is trying to find a way forward as an active coal mine and thermal power plant amidst the trend of decarbonization by continuing to present added value in the form of research and education that goes beyond the production and use of coal.

6. Conclusion

The Japanese coal mining and electric power industries have contributed to the development of coal-fired power generation and underground coal mining. The following three contributions can be noted:

The mechanization of longwall mining. In the late 1960s, Taiheiyo combined a shearer with powered supports into the "SD system." In this process, the development of a four-leg chock shield with lemniscate linkage was a technical milestone. These technical advancements were possible because Taiheiyo's mining engineers had knowledge of mine engineering and practical techniques and through the close relationship with a mining machine manufacturer, Miike Machinery. The SD system and its related technologies began to be exported abroad after the 1970s.

The transfer of technology to Asian countries. Technology transfer was implemented after the 1990s, when the Japanese coal mining industry was in a continued state of decline. Knowledge of mine safety and mine operations was transferred from Japan to coal mining industries in other Asian countries, which had suffered from decreases in mining efficiency and increases in mining accidents as economic development led to increased coal production. Technology transfer contributed to the modernization and rationalization of coal mines, although it did not provide much financial benefit to the Japanese coal mining industry.

The promotion of thermal efficiency and decarbonization of coal-fired power generation. The Japanese electric power industry succeeded not only in increasing the power-generating capacity of USC power plants but also in the commercial operation of IGCC power plants. In addition, technological developments in the combination of coal-fired power generation with CCUS at an underground coal mine were made by KCM. Large coal-consuming countries, such as China and India, replacing conventional coal-fired power plants with the most advanced ones will accelerate global decarbonization.

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