

# Estimation of Costs and Carbon Offset Credits Associated with Oil Well Plugging Based on Field-verified Natural Gas Emissions from Abandoned Wells of the Kurokawa Oil Field, Japan

Chikashi Togashi<sup>1\*</sup> and Hiroshi Nawata<sup>2</sup>

<sup>1</sup>Graduate School of International Resource Sciences, Akita University, 1-1 Tegata-gakuen-cho Akita City, Akita 010-0852, Japan

<sup>2</sup>Center for Transdisciplinary Education and Research, Graduate School of Human and Environmental Studies, Kyoto University, Yoshida-nihonmatsu-cho, Sakyo-ku, Kyoto 606-8501, Japan

**Abstract.** We estimated greenhouse gas (GHG) emissions from abandoned oil wells in the Kurokawa oil field in Akita Prefecture, Japan, to explore the potential costs and carbon offset credits associated with reducing GHG emissions. These wells were abandoned, but not capped, following technical failure by the management company, leaving crude oil and natural gas in the field. As no recent gas production records or other data exist for the Kurokawa oil wells, we estimated the amount of methane released by the wells based on old survey data and field optical gas imaging using an infrared camera. Based on these measurements, we estimated methane emissions of 7,300 t-CO<sub>2</sub>e/year, a substantial amount when compared against the 47,400 t-CO<sub>2</sub> estimated methane emissions reported for fiscal 2019 in Akita Prefecture as a whole. We found that plugging the wells would be highly effective in reducing GHG emissions. The cost per t-CO<sub>2</sub> reduction was estimated at 3,500 JPY (25 USD), based on a single-well cost of 50 million JPY, which is lower than that associated with reducing other GHGs. The potential GHG reductions from this sequestration project could be authorized as carbon offset credits, which would exceed those accumulated through energy conservation, and at lower cost. Thus, we anticipate that capping abandoned wells will represent an effective approach for securing financial resources.

## 1 Introduction

Methane is a significant greenhouse gas (GHG) emitted from both human activities—such as natural gas leakage and livestock production—and natural sources. In addition to its direct impacts on climate, it affects human health and agriculture as a precursor to tropospheric ozone. Methane has a short atmospheric lifespan of approximately 12 years, and its

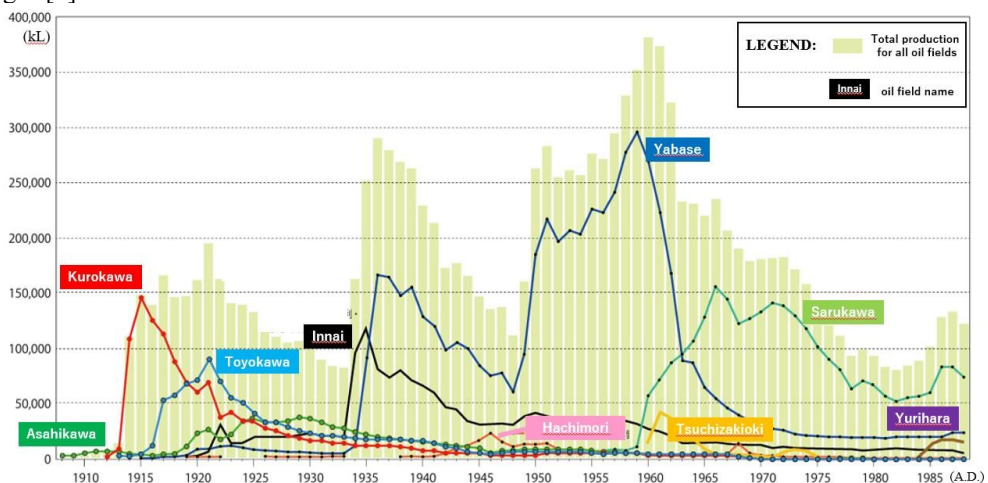
---

\* Corresponding author: [chika7262@gmail.com](mailto:chika7262@gmail.com)

greenhouse effect per unit mass is 81–83 times higher than that of CO<sub>2</sub> over 20 years and 27–30 times higher (specifically 29.8 for fossil methane) over 100 years (IPCC Sixth Assessment Report; AR6). Because methane is short-lived in the atmosphere, efforts to reduce methane emissions are expected to yield immediate climate and health benefits. At the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP26) in November 2021, the Global Methane Pledge was launched as an international framework to reduce methane emissions. Championed by the United States and European Union, it established a goal of  $\geq 30\%$  reduction from 2020 levels by 2030, which would reduce global warming by 0.2°C by 2050 and reduce the severity and frequency of extreme weather events caused by climate change. Globally,  $> 60\%$  of total methane emissions are due to human activities, of which agriculture accounts for approximately 42%, methane leakage during natural gas production and coal mining accounts for 36%, and waste accounts for 18%. Emissions from coal mining and the oil and gas sector can be reduced by  $\geq 65\%$  through measures such as preventing gas leaks from pipelines and recovering and using gas at the production stage. The IPCC Working Group I Sixth Assessment Report (2021) stated that managing methane and other GHGs is also important to limiting cumulative CO<sub>2</sub> emissions and achieving at least net-zero CO<sub>2</sub> emissions [1].

In the United States and Canada, oil and gas wells that were abandoned after the cessation of commercial production due to bankruptcy or other economic reasons have been found to continue releasing methane and other substances when no longer actively managed. Thus, the release of large amounts of methane and other substances from abandoned wells that remain unplugged or improperly plugged is a growing concern [2].

Modern oil production began in the United States more than 160 years ago, and in Japan, many oil wells have been developed since the beginning of the Meiji era (1868–1912) using foreign technologies [3]. In Japan, as in the United States and elsewhere, there have been various cases where production ceased a century or more ago, but the wells were never properly plugged and have been leaking crude oil and/or natural gas since. In oil and gas fields with no responsible administrator, the Japanese national and local governments are spending large sums of money to plug wells and prevent the release of crude oil and natural gas [4].



**Fig. 1.** Trends in crude oil production by oil field in Akita Prefecture, 1908–1988 (after [5]).

The history of oil and gas field development in Akita over the past century teaches us that at the well or field level, production peaks and then inevitably declines [5]. In Japan there is no clear legal basis for patrols or other security measures after oil field closure, forcing local

governments and volunteers to assume these responsibilities. In September 2018, the Kurokawa oil field in Akita Prefecture, went bankrupt after 130 years of oil and gas production, leaving 21 wells abandoned. This oil field, located in Kanaashi-Kurokawa, Akita, was developed in 1912 by the Nippon Oil Corporation (now ENEOS Co., Ltd.). At its peak in 1914, the field had an annual production of over 150,000 kL (approximately 940,000 barrels), and continued stable production until the early 1930s, declining thereafter (Figure 1) [5, 6].

The oil field began to produce and supply natural gas in the 1960s; however, the owners abandoned it due to financial difficulties in September 2018, leaving wells that leaked crude oil and natural gas. Although the national government and local municipalities began to systematically plug the wells due to concerns about the contamination of rivers and other waterways from leaking crude oil, the cost of plugging a single well was approximately JPY 50 million in 2021 (equivalent to approximately USD 330,000–350,000), which represents a significant financial burden. Studies in the United States, Canada, and other countries have also reported air pollution due to abandoned oil and gas wells [7], as well as land cover changes, forest fragmentation, and soil degradation in deserted oil production facilities.

This study uses infrared cameras (FLIR GF320) to image gas leakage optically and provide field-verified evidence of methane emissions from the Kurokawa oil field. We then evaluate the environmental impacts of these emissions and explore the economic viability of reducing them through carbon offset credits.

## 2 Methodology

### 2.1 Historical data and literature survey

Because there are no recent records of natural gas production at the Kurokawa oil wells, we summarized natural gas production based on surveys conducted in 1967 and 1982 by Akita University [8, 9]. The reported oil and gas production rates included natural gas produced by operating oil extraction pumps to enhance natural gas extraction further, which differs from the current rate of natural gas production from the abandoned wells. Additionally, the amounts recorded in the surveys are the production volumes of wells that were operational at the time of measurement; because some wells were shut down for maintenance, the wells covered in 1967 and 1982 were not identical (Table 1).

**Table 1.** Gas volume survey results

|                                    | 1965        | 1967         | 1982        |
|------------------------------------|-------------|--------------|-------------|
| Measurement date                   | January 6–7 | August 21–23 | October 6–8 |
| Number of wells                    | 12          | 20           | 22          |
| Total volume (m <sup>3</sup> /day) | 6,258       | 3,844        | 4,411       |

### 2.2 Field survey

We accompanied the former safety manager of the Kurokawa oil field on voluntary safety inspections and surveyed 17 of the 20 accessible wells. Kurokawa Rotary Well No. 5 was designated a “Cultural Property of Akita City” in 1968, and a commemorative marker still stands on the site today (Figure 2, 3).

The crude oil collected from the abandoned wells amounts to approximately three drums (about 0.6 kiloliters) per year. These are collected and disposed of as industrial waste by Akita City with the help of the former safety manager (Figure 3).



**Fig. 2.** (a) Landscape photograph of the Kurokawa oil field taken by the Nippon Oil Corporation and published in 1925 as a postcard, (b) map of abandoned Kurokawa oil wells studied from March 17 to May 13, 2022.



**Fig. 3.** (a) Kurokawa Rotary Well No. 5 in 1914, (b) Commemorative marker *Cultural Property of Akita City* at Kurokawa Rotary Well No. 5, (c) three drums (about 0.6 kiloliters) of crude oil collected from abandoned wells at the Kurokawa oil fields in 2022.



**Fig. 4.** Optical gas images were taken in early July 2022 using an infrared camera (FLIR GF320).

Because the original management company no longer exists and the facilities are aging, it was difficult to conduct a survey identical to those conducted previously. We used an infrared camera (model GF320; Teledyne FLIR, Wilsonville, OR, USA) to obtain optical gas images and safely measure gas leakage among the accessible oil wells (Figure 4). This

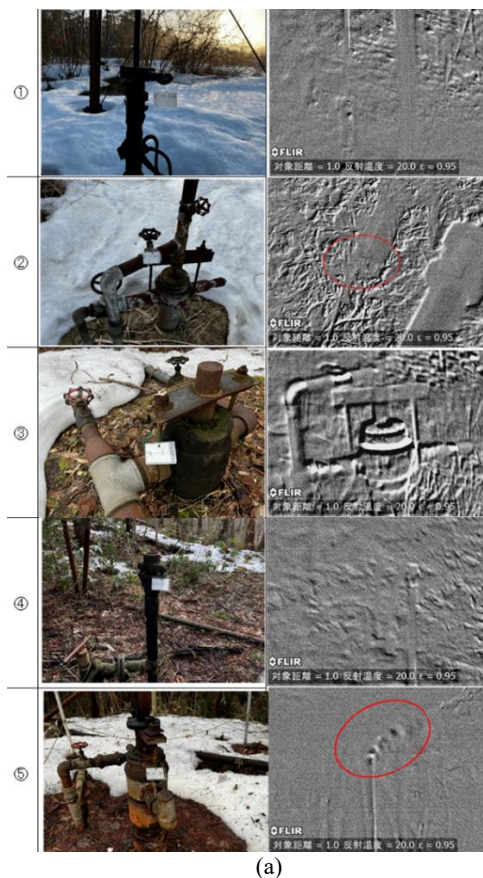
approach allowed us to conduct a basic survey while establishing a baseline for anticipated future improvements in measurement methods.

To bridge the 40-year data gap, we integrated current measurements with expert input from the former safety manager, who provided comparative context regarding the field's pressure and flow conditions in 1982 versus the present state. This integrated approach—combining historical records, optical gas imaging (OGI) visualization, and direct spot-measurements—was used to estimate the current total methane discharge from the Kurokawa oil field.

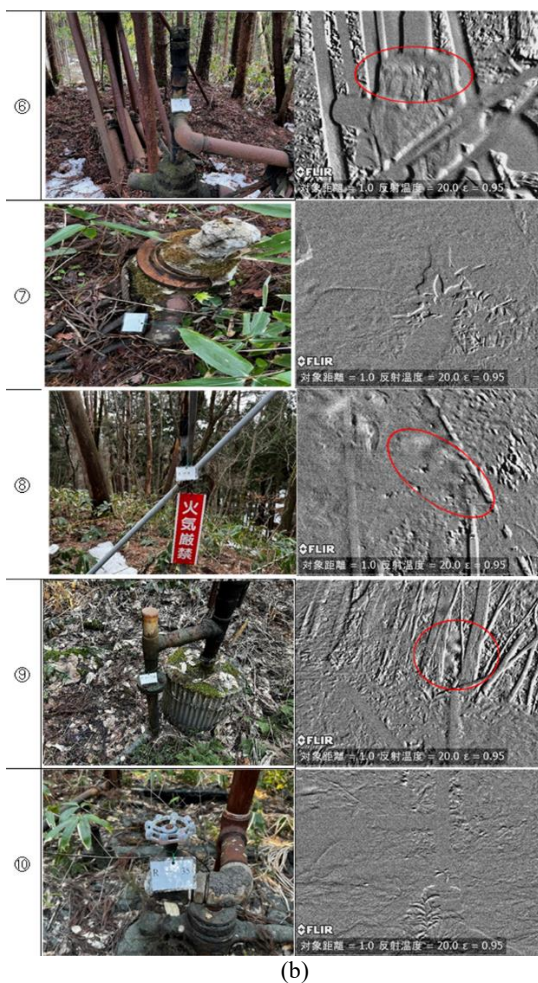
### 3 Results

#### 3.1 Direct observations with optical gas imaging

The OGI survey identified diverse methane leakage patterns across the Kurokawa oil field. High-volume, continuous emissions were visually confirmed at three wells: C104, R008, and R015. In contrast, well R005 exhibited only minor leakage, likely due to degraded but partially functional wellhead components (see Table 3 for Well ID). Gas was being discharged upward, and we confirmed there were no malfunctions in the pipes or other components along the way (Figure 5).



**Fig. 5.** (a) Images of five abandoned wells (Well No.1 to 5) at the Kurokawa oil field. Photographs were taken from mid-March to early May 2022.

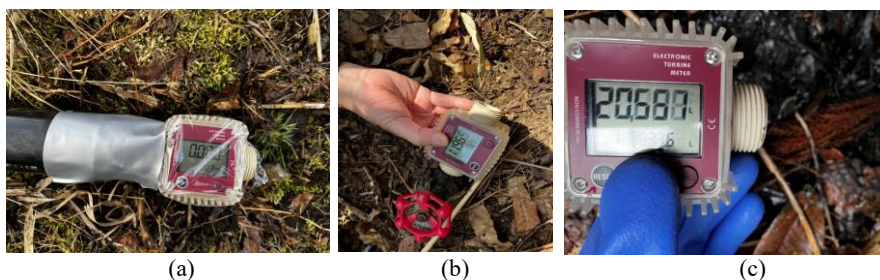


**Fig. 5.** (b) Images of five abandoned wells (Well No.6 to 10) at the Kurokawa oil field. Photographs were taken from mid-March to early May 2022.

Comprehensive measurements at some locations were constrained by site safety risks, including the presence of wild animals (e.g., Asian black bears).

### 3.2 Emission quantification and field measurements

Direct flow measurement was technically restricted by the absence of mineral rights holders and the advanced deterioration of wellhead infrastructure, which prevented the installation of airtight, inline flowmeters. To mitigate exposure risks and equipment damage, an electric turbine flowmeter was utilized for short-term measurements of effluent (oil and water) at accessible points (Figure 6).



**Fig. 6.** Flowmeter installation for gas flow rate measurements at (a) well C113 (broken pipe), (b) well R008 (drain outlet), and (c) well C104 (drain outlet).

The measured flow rates for the primary leaking wells are summarized in Table 2.

**Table 2.** Measured flow rates for the primary leaking wells.

| Measurement location                      | Date           | Flow rate  | 24-h conversion          |
|---|----------------|------------|--------------------------|
| Broken gas transmission pipe in well C113 | April 22, 2022 | 4–5 L/min  | 6 m <sup>3</sup> /day    |
| Drain outlet of well R008                 | April 12, 2022 | 18 L/min   | 25.9 m <sup>3</sup> /day |
| Drain outlet of well C104                 | April 15, 2022 | 36.6 L/min | 48.3 m <sup>3</sup> /day |

At well C113, we obtained measurements from a broken gas pipe; the gas leaked from a gap between the flowmeter and the pipe mouth, resulting in some variation; however, we measured the gas release rate at approximately 6 m<sup>3</sup>/day. This discharge level has likely remained relatively constant for > 50 years. Stable values were measured at open drain outlets of the R008 and C104 wells; however, according to the former safety manager, our measured gas flow rates for these wells may be approximately one eighth of the actual discharge, as the selected outlets represent only part of the flow from the original discharge port. There was also gas leakage from a gap between the flowmeter and the drain opening at these two wells. The gas flow rates measured at wells C104, R008, and R015 are listed in Table 2.

Synthesizing field measurements, OGI observations, and expert historical knowledge, we estimated the current total methane discharge to be approximately 50% of 1982 levels. This reduction is attributable to the cessation of active pumping and the gradual decline in reservoir pressure over time. The integrated estimates for each well are presented in Table 3.

**Table 3.** Estimated Kurokawa oil field emissions.

| Well No. | Well ID | Emissions (m <sup>3</sup> ) |       |            | Current well status                  |
|----------|---------|-----------------------------|-------|------------|--------------------------------------|
|          |         | 1967                        | 1982  | Estimation |                                      |
| 1        | C124    | 17                          | –     | –          | Almost no emission                   |
| 2        | C113    | 5                           | 23    | 9          | Emitting 5 L/min                     |
| 3        | R006    | –                           | –     | –          | No emission                          |
| 4        | C001    | 179                         | –     | –          | No emission                          |
| 5        | R015    | 210                         | 150   | 80         | High emission                        |
| 6        | R005    | –                           | –     | –          | Low emission (optical gas imaging)   |
| 7        | R077    | –                           | –     | –          | No emission                          |
| 8        | R008    | 445                         | 156   | 150        | Emitting 18 L/min from drain port    |
| 9        | C104    | –                           | 533   | 250        | Emitting 33 L/min from drain port    |
| 10       | R035    | 96                          | 130   | –          | No emission                          |
| 11       | C142    | 632                         | 296   | –          | No emission                          |
| 12       | C081    | –                           | –     | –          | No emission                          |
| 13       | R138    | 10                          | –     | –          | No emission                          |
| 14       | R018    | 87                          | 297   | 150        | High emission                        |
| 15       | R097    | –                           | 19    | –          | No emission                          |
| 16       | R102    | –                           | –     | –          | No emission                          |
| 17       | R045    | 12                          | 31    | –          | No gas detected at drain port        |
| 18       | R094    | 467                         | 1,029 | 450        | Inaccessible, high emission reported |
| 19       | C108    | 95                          | –     | –          | Inaccessible                         |
| 20       | C131    | –                           | –     | –          | Inaccessible                         |
| Total    |         | 2,255                       | 2,664 | 1,089      |                                      |

### 3.3 Compositional analysis of released gas

During our literature review, we found a record of composition analysis based on gas chromatography conducted by the Akita Gas Bureau in September 1982, although the sampling location is unknown. We also analyzed gas collected from a drain outlet of the R008 well in April 2022 using gas chromatography, and found that its composition was very similar to that recorded in 1982. This analysis was conducted on April 27, 2022, with collection and analysis contracted to NS Environmental Co. (Table 4).

**Table 4.** Compositional analysis of gas emitted from wells at the Kurokawa oil field. The location of the well sampled in 1982 is unknown; Well R008 was sampled in 2022.

|                | September 1982 | April 2022 (R008) |
|----------------|----------------|-------------------|
| Methane        | 85.73%         | 87.0%             |
| Carbon dioxide | 8.39%          | 7.5%              |
| Ethane         | 0.75%          | Not detectable    |

### 3.4 GHG calculations

We accompanied the former safety manager of the Kurokawa oil field on volunteer safety inspections and surveyed 17 of the 20 accessible wells (Figure 2, 3). Based on infrared camera imaging, we estimated the volume of emissions from the Kurokawa oil field to be approximately 1,100 m<sup>3</sup>/day. Therefore, we calculated yearly GHG emissions from the oil field as follows:

$$\text{Gas discharge rate (1,100 m}^3\text{/day)} \times \text{Methane concentration (85\%)} \times \text{Methane gas density at 0}^\circ\text{C and 0.1 MPa (0.717 kg/ m}^3\text{)} \times 365 \text{ days} \times \text{Global warming potential (29.8)} = 7,302.7 \text{ t-CO}_{2e},$$

where the global warming potential of methane is assumed to be 29.8 times that of CO<sub>2e</sub> based on a methane concentration of 85% [10]. Thus, the annual volume of GHG emissions from the oil field is estimated at 7,302.7 t-CO<sub>2e</sub>.

## 4 Discussion

### 4.1 Cost-effectiveness

In this study, we attempted to quantify the environmental impact of ongoing emissions from abandoned gas wells in the Kurokawa oil field, where it has been impossible to conduct precise on-site measurements. Although a 15-year production period was assumed at the start of production, the field has been leaking methane for approximately 60 years, and is expected to continue doing so.

**Table 5.** Estimated methane emissions at the Kurokawa oil field, compared with those of Akita Prefecture and Japan as a whole.

|                                | Annual emissions (t-CO <sub>2e</sub> ) |
|--------------------------------|--|
| Kurokawa                       | 7,300                                  |
| Akita (excluding Kurokawa)     | 47,400                                 |
| Total methane leakage in Japan | 690,000                                |

Methane emissions from the oil field were estimated at 7,300 t-CO<sub>2e</sub> per year, which is not insubstantial compared to the estimated 47,400 t-CO<sub>2</sub> of methane generated in fiscal 2019,

per the GHG emissions data reported for Akita Prefecture. The total methane released by the abandoned Kurokawa oil wells represents < 1% of Japanese methane fuel leakage from processes such as natural gas production and coal mining, which was estimated at 690,000 t-CO<sub>2</sub> in fiscal 2019 [11]. However, the abandoned wells are expected to continue to discharge methane at this rate indefinitely if they are not properly plugged, and their cumulative environmental impact will be considerable (Table 5).

Based on past oil field projects in Akita, the cost per well to plug the Kurokawa oil wells would be approximately JPY 50 million (USD 330,000), with a total cost for all 20 wells exceeding JPY 1 billion (USD 6.6 million). However, if the oil wells were to be plugged over an 8-year period, that cost would be for a total of 274,500 tons of GHGs released, assuming a yearly reduction of 0.125 tons and a 1-ton GHG reduction cost of JPY 3,500 (USD 23). For fiscal 2021, the Japan Ministry of the Environment estimated the average CO<sub>2</sub> reduction cost at JPY 16,451 (USD 108) /t-CO<sub>2</sub>/year [12] (Table 6).

**Table 6.** GHG reduction costs for plugging the Kurokawa oil wells.

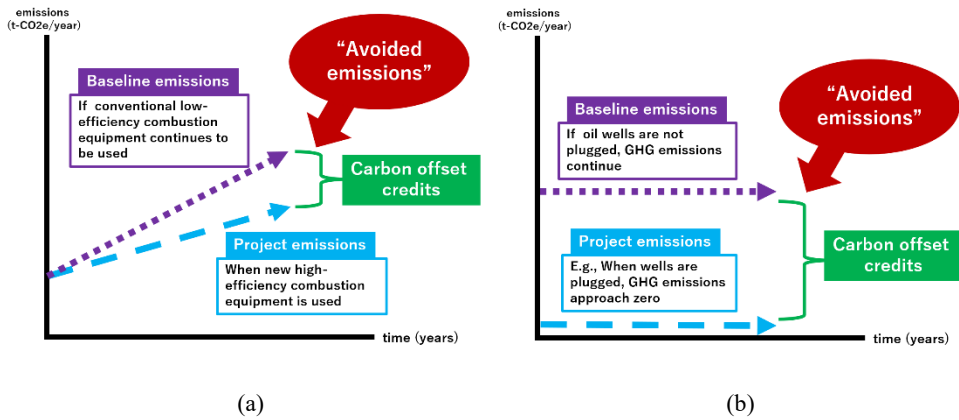
|                            | <b>Annual emissions (t-CO<sub>2</sub>)</b> |
|----------------------------|--|
| Plugging cost per well     | JPY 50 million (USD 330,000)               |
| Total plugging cost        | JPY 1 billion (USD 6.6 million)            |
| GHG reduction cost per ton | JPY 3,500 (USD 23)                         |

## 4.2 Carbon offset potential

The potential GHG reductions from this sequestration project could be justified as carbon offset credits, which would exceed those accumulated through energy conservation, and at lower cost. Thus, we anticipate that capping abandoned wells will represent an effective approach for securing financial resources. Because the lifespan of atmospheric methane is approximately 10 years and plugging wells is certain to reduce GHG emissions, it would be highly beneficial to prioritize the plugging of wells that continue to emit large amounts of methane. Although some wells currently emit low amounts of GHGs, it is desirable to resolve all wells in the oil field as soon as possible, as wellheads, access roads, storage tanks, and other structures continue to fragment plant and animal habitats and worsen the effects of erosion and storm water runoff.

We benchmarked the science-based offset methodologies provided by the American Carbon Registry (ACR)—specifically the *Methodology for the Quantification, Monitoring, Reporting and Verification of Greenhouse Gas Emissions Reductions and Removals from the Plugging of Orphaned Oil and Gas Wells*—to verify its applicability to the Kurokawa oil field. To issue carbon offset credits, the ACR methodology establishes that three primary requirements must be satisfied for each project: (1) *setting the assessment boundary*, (2) *establishing the baseline*, and (3) *demonstrating additionality* [13].

Accurately quantifying GHG reductions requires defining the *boundary* of emission and removal sources. Following the ACR methodology, our study focuses on direct emissions from wells, excluding ancillary facilities such as storage tanks. For the Kurokawa oil field, although it would be ideal to cover all abandoned wells sharing the same reservoir, limiting the scope to wells within the mining lease targeted for our project is practical and justified by the lack of observed interference with other wells. This boundary ensures accurate measurement and eliminates double counting.



**Fig. 7.** Carbon offset credits by setting the baseline and avoided emissions for each project: (a) GHG reduction through high-efficiency boiler installation, (b) GHG reduction through abandoned oil well plugging (after [13]).

The *baseline* represents the most plausible emission scenario if the proposed project is not conducted (Figure 7). The ACR methodology sets out a rigorous process for determining the baseline: 12 consecutive measurements at 10-minute intervals, followed by re-measurement after at least 1 month. Preliminary surveys at the Kurokawa oil field showed that the deviation of measured values remained within 10%, suggesting that establishing a baseline through this strict protocol is feasible.

Demonstrating *additionality* ensures that the project goes beyond regulatory requirements and common practice. From a regulatory perspective, while the Mine Safety Act mandates safety measures for 5 years after closure, many wells lack responsible managers due to bankruptcy. Thus, plugging for GHG reduction purposes beyond legal obligations is a novel initiative. Furthermore, the absence of emissions from abandoned wells in Japan’s National GHG Inventory suggests that such activities are not yet established as common practice. From an economic perspective, creating a mechanism to utilize carbon credits as a new financial resource, replacing the current total reliance on government funding, constitutes economic additionality. However, challenges remain for registration under systems like the J-Credit scheme, such as the prerequisite of being included in the national inventory.

## 5 Conclusion

The current laws and regulations of Japan do not specify who is responsible for the future monitoring costs of abandoned oil wells. Although the initial oil production plan for the Kurokawa oil field anticipated a lifetime of 15 years, no corresponding closure or mitigation plan was created. It is necessary for oil and gas companies to create permanent management plans to avert the problems associated with abandoned oil wells, which affect not only the oil and gas industry but also other industries such as mineral water treatment facilities or landfill sites in Japan [13].

By integrating high-resolution satellite data with in situ field survey measurements, we have also initiated a comprehensive satellite-based methodology for monitoring methane leakage from abandoned oil wells at the former Kurokawa oil field, using multi-band multi-pass Sentinel 2 SWIR band 11 and 12. Sentinel-2 SWIR Bands 11 (approx. 1560–1660 nm) and 12 (approx. 2090–2290 nm) feature a spatial resolution of 20 m. This resolution enables

detailed characterization of the spatial distribution of small methane point sources near the Earth's surface [14].

If the Kurokawa oil well plugging project is applied to future carbon offsetting, it will be necessary to estimate GHG emissions accurately from this site. Low-cost plugging methods that are less damaging to the natural environment must also be developed. The resolution of abandoned oil wells is a necessary component of Japanese policies, especially in the context of Japan's falling birthrate and aging population, and the decline of local industries. This issue will continue to be a major challenge for Japan in the future. We hope that the Kurokawa oil well plugging project will contribute positively to Japanese environmental management.

Over the past half-century, Japanese society has relied almost entirely on imports from abroad and has generally failed to properly address its own domestic oil and gas resources. In particular, scientists and engineers researching global resources, along with the business community that depends on energy and metal resources, have not taken the lead in illuminating the challenges at their proverbial doorstep. We cannot simply abandon the sites of past underground resource development, having ceased to generate profits. Production may have ended but responsibility continues; therefore, so must management. Integrated resource management at underground resource development sites must continue as a pillar of humanity's overarching imperative to coexist with the natural world [15].

In this study, we estimated greenhouse gas (GHG) emissions from abandoned oil wells in the Kurokawa oil field in Akita Prefecture, Japan, to explore the potential costs and carbon offset credits associated with reducing GHG emissions. These wells were abandoned, but not capped, following technical failure by the management company, leaving crude oil and natural gas in the field. As no recent gas production records or other data exist for the Kurokawa oil wells, we estimated the amount of methane released by the wells based on old survey data and field optical gas imaging using an infrared camera. Based on these measurements, we estimated methane emissions of 7,300 t-CO<sub>2</sub><sub>e</sub>/year, a substantial amount when compared against the 47,400 t-CO<sub>2</sub> estimated methane emissions reported for fiscal 2019 in Akita Prefecture as a whole. We found that plugging the wells would be highly effective in reducing GHG emissions. The cost per t-CO<sub>2</sub> reduction was estimated at 3,500 JPY (25 USD), based on a single-well cost of 50 million JPY, which is lower than that associated with reducing other GHGs. The potential GHG reductions from this sequestration project could be authorized as carbon offset credits, which would exceed those accumulated through energy conservation, and at lower cost. Thus, we anticipate that capping abandoned wells will represent an effective approach for securing financial resources.

How should we manage the leakage of 0.6 kiloliters of crude oil and the emissions of 7,300 t-CO<sub>2</sub><sub>e</sub> of methane per year from abandoned oil wells that should have ceased production? We believe that confronting this challenge head-on now holds significant meaning for Japanese society as well as global communities.

## **Acknowledgments**

This work was supported by JSPS KAKENHI Project Grant Number 25K03325 "Verification of abandoned oil well plugging effects for carbon offset credits by precise measurement of methane emissions" and RIHN IS studies 2022 "Transdisciplinary research on indigenous/traditional knowledge of natural resource management and human-livestock relationships". We extend our gratitude to the Conference Organizing Committee of the 12th International Conference on Environment and Renewable Energy (ICERE 2026) for awarding us the Best Presentation award, which provided strong motivation to continue our work.

## References

1. J.G. Canadell, P.M.S. Monteiro, M.H. Costa, L. Cotrim da Cunha, P.M. Cox, A.V. Eliseev, S. Henson, M. Ishii, S. Jaccard, C. Koven, A. Lohila, P.K. Patra, S. Piao, J. Rogelj, S. Syampungani, S. Zaehle, K. Zickfeld, Global Carbon and Other Biogeochemical Cycles and Feedbacks, in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge, UK, Cambridge University Press, 2021)
2. M. Kang, A.R. Brandt, Z. Zheng, J. Boutot, C. Yung, A.S. Peltz, R.B. Jackson, Orphaned Oil and Gas Well Stimulus—Maximizing Economic and Environmental Benefits, *Elementa* **9**, 00161 (2021)
3. T. Ikegami, M. Nakazawa, R. Nishizawa, Japan Oil Mining History: History of Oil Field Development and Exploration. *Journal of the Japanese Association for Petroleum Technology* **18**, 126–141 (1953)
4. Japan Ministry of Economy, Trade and Industry, Costs of Subsidizing the Capping of Abandoned Oil Wells (Japan Ministry of Economy, Trade and Industry, 2003)
5. Akita Prefectural Archives, Oil Development in Akita as Seen in Official Documents (Akita, Akita Prefecture Archives, 2016)
6. K. Fujioka, Oil Fields in Akita (Akita, Akita Sakigake Shimposha, 1983)
7. R.K. Lattanzio, Methane and Other Air Pollution Issues in Natural Gas Systems (Washington, DC, Congressional Research, 2020).
8. S. Tanaka, Expert Report on Gas Reserves in the Kurokawa Oil Field (Faculty of Mining, Akita University, 1942).
9. K. Taniguchi, Report on the Survey of Gas Production from the Kurokawa Oil Field Wells: Survey Conducted in October 1982 (Faculty of Mines, Akita University, 1982).
10. Japan Ministry of Economy, Trade and Industry, Ministry of the Environment, Greenhouse Gas Emissions Calculation and Reporting Manual 4.8 (Japan Ministry of Economy, Trade and Industry, Ministry of the Environment, 2022)
11. National Institute for Environmental Studies, Greenhouse Gas Emissions for FY2020, (Japan Ministry of the Environment, 2022)
12. Japan Ministry of the Environment, CO<sub>2</sub> Reduction Effect of Global Warming Countermeasure Taxes: Update of Trial Calculations at the 8th Subcommittee Meeting (Japan Ministry of the Environment, 2021)
13. C. Togashi, Greenhouse Gas Emissions from Orphaned Gas Wells in Kurokawa Oil Field, Akita City, Japan: Estimation, Environmental Impact, and Public Works Potential for Mitigation, *People and Environment* **51**, 3–14 (2025)
14. B. Hoshino, C. Togashi, H. Nawata, *Feasibility of Detecting Low-Level Methane Emissions from Abandoned Oil Wells Using a Multi-Band, Multi-Pass Satellite Approach*, in Proceedings of the 12<sup>th</sup> International Conference on Environmental and Renewable Energy, February 28–March 2, 2026, Nha Trang, Vietnam (2026)
15. H. Nawata, Facing Japan's Crude Oil and Natural Gas Today: Production Ended, Management Continues, *Kikan Minzokugaku* (Ethnology Quarterly) **190**, 12–22 (2024)