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A COMPREHENSIVE STUDY ON TECHNOLOGICAL SOLUTIONS FOR ASSOCIATED GAS GATHERING, TREATMENT, AND UTILIZATION AT OFFSHORE FIELDS OPERATED BY VIETSOVPETRO

Le Viet Dung, Nguyen Lam Anh, Nguyen Anh Phong, Nguyen Quoc Dung, Chu Van Luong, Nguyen Hoai Vu
Vietsovpetro Joint Venture
Email: vunh.pt@vietsov.com.vn
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Summary

In 1986, after nearly 5 years of exploration, Vietsovpetro successfully produced its first crude oil from the Bach Ho field, located in Block 09-1 of the Cuu Long basin on the Vietnamese continental shelf. This milestone marked a historic breakthrough for Vietnam's petroleum industry, positioning the country among the oil-producing and exporting nations and laying the foundation for the development of the modern Vietnamese oil and gas sector.

In 1995, Vietsovpetro achieved another significant milestone by pioneering the gathering, treatment, and onshore transportation of associated gas through innovative technological solutions and engineering improvements, despite limited offshore infrastructure at the time. This initiative marked the second major leap in Vietnam's petroleum industry and served as the technological and operational foundation for the subsequent establishment and growth of the Petrovietnam Gas Joint Stock Corporation (PV GAS).

This article presents the key technical highlights of a cluster of projects on associated gas gathering and utilization implemented by Vietsovpetro at offshore fields in Block 09-1 and adjacent offshore fields.

Key words: Associated gas, gas gathering, gas treatment, Block 09-1, Bach Ho field.

1. Introduction

In the 1940s, countries such as the United States, Norway, and Canada utilized up to 70% of the associated gas separated from crude oil production for processing, power generation, and other applications. Over the subsequent decades, these countries have significantly improved their gas recovery efficiency and currently utilize more than 95% of their associated gas. Major international oil companies, including Chevron (USA), TotalEnergies (France), and Shell (UK and the Netherlands), have achieved nearly 100% associated gas utilization in their field developments [1].

In contrast, the former Soviet Union (now the Russian Federation) historically prioritized crude oil production, and associated gas often was flared at the field site. However, since the early 2000s, driven by economic development and global environmental commitments, the Russian government has implemented stricter regulations, mandating associated gas utilization levels of up to 95% for new field developments.

Maximizing associated gas recovery is a crucial component of sustainable hydrocarbon development. Many governments now require oil and gas operators to submit a detailed plan for gathering and utilizing associated gas in investing and developing oil fields. Compliance with these regulations has become a key criterion for governments to grant or suspend oil and gas exploration and production licenses in regions and territories.

The Bach Ho oil field, located in Block 09-1 of the Cuu Long basin, was initially designed, constructed, and developed primarily for oil extraction, with the associated gas being flared directly on offshore platforms [2]. As a result, between 1986 and the first quarter of 1995,

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Vietsovpetro flared more than 6 billion cubic meters of associated gas, equivalent to approximately 6 million tons of oil. During this period, Vietnam was experiencing a severe energy crisis. Each year, Vietnam imports diesel oil (DO), fuel oil (FO), and liquefied petroleum gas (LPG) to meet domestic energy demands. The Ba Ria thermal power plant, located only 120 kilometers from the Bach Ho field, depended entirely on imported DO and FO for electricity generation. Moreover, the country was still under international embargo, facing acute shortages of foreign currency and undergoing profound economic and social hardship.

The continuous flaring of associated gas not only resulted in the loss of a valuable non-renewable national resource but also had adverse environmental impacts, contributing to air pollution and ecological degradation in oil-producing regions. Addressing the technical and economic challenges of gathering and utilizing associated gas thus became an urgent and strategic objective for the Petrovietnam, and particularly for Vietsovpetro.

In 1995, Vietsovpetro initiated the gathering of associated gas for utilization at offshore facilities, with the remaining volume transported ashore. By September 30, 2025, Vietsovpetro had gathered, treated, and delivered approximately 40.3 billion cubic meters of associated gas to onshore facilities, of which more than 23.5 billion cubic meters of gas had been used to meet the industrial development of Vietnam's gas, electricity, fertilizer, petrochemical value chain, and serving residential and industrial needs. The success of this initiative has established a reliable foundation for the long-term growth of the Vietnamese gas industry.

2. Technological solutions for associated gas gathering, treatment, and transportation at Vietsovpetro's and adjacent fields

In 1991, with the approval of the Government, Vietsovpetro developed a technical and economic feasibility study titled "Gathering and transportation of associated gas from the Bach Ho field to shore", with the following key points:

- Efficient utilization of fuel resources was identified as one of the urgent tasks for Vietnam's economic and social development;

- Associated gas from offshore facilities in Block 09-1 needed to be gathered and utilized to the maximum extent;

- The main content of the feasibility study was to develop a program for transporting gas to shore for use as fuel in thermal power plants in southern Vietnam.

The implementation of the project for gathering and transporting associated gas from the Bach Ho field to Thu Duc, Ho Chi Minh City, was estimated to take approximately 8 to 10 years.

Based on an assessment of existing infrastructure and field conditions at the offshore Bach Ho Field, Vietsovpetro initiated research into technological solutions for the early gathering and transportation of associated gas to shore, despite the absence of gas compression facilities at that time.

2.1. Solution for the early associated gas gathering and transportation of 1 million stm^3/day from the Bach Ho field to shore without using compressors

To implement the associated gas gathering and transportation project from the Bach Ho Field, Vietsovpetro proposed to construct the Bach Ho - Dinh Co - Ba Ria gas pipeline, with a total length of 120 km and a diameter of 406 mm.

Vietsovpetro conducted research on technological solutions and carried out offshore trials to assess the feasibility of gathering and transporting 1.0 million stm^3/day of associated gas from the Bach Ho field to the Ba Ria thermal power plant, utilizing the natural energy of oil wells in conditions where gas compressors were not yet available:

- Hydraulic calculation for the transportation of 1.0 million stm^3/day of associated gas through the 120 km pipeline (406 mm diameter), from the Bach Ho Field to the Ba Ria thermal power plant, showed a pressure loss of approximately 17 - 18 atm.

- Given that the required gas pressure at the onshore receiving point was 20 atm, the necessary inlet pressure at the offshore end had to be 38 - 40 atm. Vietsovpetro conducted experiments to separate gas from high-pressure, high-flow oil wells. The results indicated that gas separated from the oil-gas mixture produced from the basement formation at the wellhead platform BK-2 yielded approximately 1.0 million stm^3/day of associated gas at 38 - 40 atm.

- With an inlet gas pressure of around 40 atm and a flow rate of 1.0 million stm^3/day, Vietsovpetro successfully transported the gas through the Bach Ho - Dinh Co - Ba

Ria pipeline, via Gas Distribution Station (GDS) at Ba Ria, and delivered it to the Ba Ria thermal power plant starting from the second quarter of 1995.

2.2. Solution for drying associated gas from the Bach Ho field without using a heat exchanger for onshore transportation

The implementation of the above solution showed that the gas separated at the wellhead platform BK-2 had a temperature of 90 - 100°C and a pressure of 38 - 40 atm, which was transported to shore through a subsea pipeline, where the temperature averaged around 25 - 28°C. Upon reaching the shore, the gas had been cooled, and liquids that had condensed along the pipeline caused the gas stream to arrive at shore in a two-phase (liquid-gas) form, which did not meet the fuel requirement for the Ba Ria thermal power plant. While the Central Processing Platform No.2 (CPP-2) did not have a heat exchange system, Vietsovpetro developed a gas dehydration solution offshore by passing the gas stream through a subsea pipeline loop from BK-2 to BK-3 and then back to BK-2. As the gas circulated through the subsea loop, it was naturally cooled by the seawater, causing it to become a two-phase form which was then sent to a slug catcher, a liquid separator already installed on the CPP-2 platform (nearby BK-2), to separate the liquids. The gas exiting the slug catcher was in single-phase (dry gas) form and was routed into the Bach Ho - Dinh Co pipeline for transportation to the Ba Ria thermal power plant. As a result, the gas reaching the power plant had a temperature of at least 25 - 28°C and was in dry form, thus meeting the fuel specifications required by the Ba Ria thermal power plant.

2.3. Solution to increase gas flow to 2 million stm³/day for onshore transportation

The complete gas compression station (CGCS) at the Bach Ho field was constructed adjacent to the MSP-4 platform and officially commenced operation in February 1997. With a capacity of 1 million stm³/day and an output pressure of 105 atm, it was primarily designed to supply gas for internal consumption within the Bach Ho field. At that time, the Phu My 1 thermal power plant had been built and came into operation, and the onshore gas demand increased to 2 million stm³/day. According to the calculation for pipeline pressure to transport 2 million stm³/day from the offshore to Phu My Plant, the minimum required gas pressure at Bach Ho offshore must be around 58 - 60 atm. To meet this requirement, Vietsovpetro researched and implemented a technological solution utilizing an ejector (gas mixing device) to blend two streams of gas: high-pressure gas steam (105 atm) from the CGCS and a low-pressure gas stream (28 atm) after preliminary separation (UPOG) on the BK-2 platform. As a result, a medium-pressure gas stream was obtained.

By mixing 1 million stm³/day of high-pressure gas from CGCS with 1 million stm³/day of low-pressure gas after UPOG using the ejector, a combined stream of 2 million stm³/day was obtained at a pressure of approximately 60 atm, which was sufficient to transport to shore, supplying both the Phu My 1 and Ba Ria thermal power plants.

At that time, the ejector installed by Vietsovpetro was the largest offshore gas mixing device ever deployed on offshore facilities worldwide, a specifically designed technological solution for long-distance gas transportation.

2.4. Solution for low-pressure gas gathering at Bach Ho field

The low-pressure gas separated on platforms at the Bach Ho field typically had pressures ranging from 0.5 to 1.5 atm, and was flared at the individual platform flare stacks because it could not be gathered economically due to the high cost of installing compression systems. To recover and utilize this low-pressure gas, Vietsovpetro studied and implemented a solution for transporting gas-saturated oil (oil containing dissolved gas) between the platforms. Specifically, oil at each platform was separated at a high-pressure separator (on the separator in the first stage), then the saturated oil was transferred to another nearby platform without passing through a low-pressure separator or pump. Finally, the oil was routed to a designated gathering platform, as detailed below [3]:

- Low-pressure gas gathering at platform MSP-4: Production fluids from MSP-7, MSP-5, and MSP-3, after passing through high-pressure separators (first stage), were transferred as gas-saturated oil to MSP-4 via the pipeline sequence MSP-7 → MSP-5 → MSP-3 → MSP-4. At MSP-4, second-stage separation was carried out, recovering low-pressure gas (0.5 - 1.0 atm) from those platforms and from portions of MSP-6 and MSP-4 itself. A booster compressor with a capacity of 18 thousand stm³/day was installed on MSP-4 to compress this low-pressure gas to 6 - 7 atm, which was then sent to the CGCP compression platform and further compressed to 105 atm.

- Gathering low-pressure gas at platform MSP-9: Similarly to MSP-4, on MSP-10, production fluids from BK-15 and MSP-10 were separated at the first stage, and the gas-saturated oil was then transferred to MSP-9, where low-pressure gas (0.5 - 1.5 atm) was separated in a second-stage separator. A booster compressor with a capacity of 18 thousand stm^3/day was installed on MSP-9 to compress the low-pressure gas to 13 - 14 atm, and it was then transferred to the Central Compression Platform (CCP).

- Gathering low-pressure gas at CPP-2 and CPP-3: At the central processing platforms CPP-2 and CPP-3, low-pressure gas was separated from production fluids of all BK platforms at the Bach Ho field. Significant volumes of low-pressure gas were separated at these platforms. To gather all the low-pressure gas separated from CPP-2 and CPP-3, Vietsovpetro proposed and implemented the installation of gas compression stations with a capacity of 150 thousand stm^3/day per platform. The gas was compressed to 12 - 13 atm and then transferred to the CCP next to CPP-2 for further compression up to 125 atm.

By using this method of transferring saturated oil without pumps and installing booster compressors on fixed platforms such as MSP-4, MSP-9, CPP-2, and CPP-3, Vietsovpetro successfully gathered 90 - 95% of the associated gas separated from the oil production facilities at Bach Ho field, Block 09-1.

2.5. Solution for gathering remaining associated gas from the Rong field after DGCP went into operation

In 2010, the Rong gas compression platform (DGCP), with a capacity of 1 million m^3/day, went into operation. As crude oil production volume in the Rong field increased significantly with the commissioning of new production platforms (e.g., RC-5, RC-9), the volume of associated gas separated exceeded the gathering capacity of DGCP.

The associated gas that could not be gathered at DGCP was typically flared on platforms at Rong field. Vietsovpetro studied and implemented the following solutions for gathering associated gas [4]:

- High-pressure gas gathering and transportation to Bach Ho: High-pressure gas from the Rong field was gathered and transported to the Bach Ho compression platform using an existing pipeline (formerly used for oil transportation), along the route RP-2 → RC-1/3 → BK-2 → CPP-2 without gas compressors. From October 2011 to December 2012, Vietsovpetro successfully gathered and transported 64.6 million stm^3 of associated gas from Rong field to Bach Ho field.

- Installation of booster compressors for remaining gas: To gather additional the remaining gas after DGCP began operation, Vietsovpetro proposed and installed two booster compressors - one on DGCP and another on RP-3 platform - each with a capacity of 500 thousand stm^3/day. From November 2013, the booster compressor on DGCP started operating, followed by the booster compressor on RP-3, enabling the gathering of an additional 1.0 million stm^3/day of Rong field gas for transfer to the Bach Ho field. This gas would have been otherwise flared in Rong field. The solution not only helped optimize resource use but also reducing the environmental impact associated with gas flaring.

3. Application of research in production practice at Vietsovpetro

3.1. Technological solutions utilizing associated gas at Vietsovpetro's oil fields

3.1.1 Utilizing associated gas for oil and gas production via gas-lift without using compressors

Based on experience and mechanical lifting methods currently applied worldwide, Vietsovpetro has gradually researched and tested various lifting methods in crude oil production at the Bach Ho field, Block 09-1 [4]:

- A pilot study was conducted using submersible hydraulic piston pumps and screw pumps at wells 21 and 28 on the fixed platform MSP-1, Bach Ho field. Due to high-temperature wells, long operational times, and high levels of mechanical impurities in the produced fluids, the equipment frequently shuts down. The pilot test was unsuccessful, and the method proved ineffective.

- A pilot study of electric submersible pumps (ESP) was conducted in 10 wells at the Bach Ho field, the results showed that presence of mechanical impurities and sand in the produced fluids frequently caused pumps to fail and burn out, leading to low efficiency and frequent repair and replacement.

- Testing of combined ESP and gas-lift systems was carried out at 3 wells in the Bach Ho field and 6 wells on the RP1 platform at the Rong field. None of the tests was effective.

- A pilot study was conducted on the gas-lift method without a compressor on platform MSP-1 by using high-pressure gas separated from high-rate and high-pressure

wells (such as wells 401 and 403/MSP-1) to inject into low-rate wells with poor natural flow. The results showed that gas-lift method operated stably, extended production time, and were independent of sand and contaminants, equipment limitations, and power on platforms. The total amount of crude oil produced using this gas-lift method without a compressor reached 81,660 tons, with approximately 24,702,150 m^3 of compressed gas utilized.

Since 1997, Vietsovpetro has implemented the gas-lift technology on a wide scale. Consequently, the central compression platform (CCP) at the Bach Ho field was put into operation in August 1997, supplying high-pressure gas (125 atm), and enabling extended gas-lift applications across Vietsovpetro's fields. This success significantly improved well productivity and oil recovery factors for fields in Block 09-1. It also served as a valuable reference for oil operators to apply not only on the Vietnamese continental shelf but also across Southeast Asia.

3.1.2. Utilizing associated gas as fuel for power generation and centralizied power supply on offshore facilities

Initially, under the 16716 "Korall" design model for developing the Bach Ho field, the offshore power supply system relied on independent diesel-powered generator stations, including DGRA 500/500 and AMAN (800 kW) diesel generators, as well as 6ЧН-25/34/8ЧН-25/34 electric engines installed on platforms.

Vietsovpetro researched and gradually implemented the use of associated gas as a fuel source for offshore power systems, through the following key initiatives [5]:

- Vietsovpetro transitioned from diesel to associated gas in power generation systems on offshore facilities in Block 09-1, including both the Bach Ho and Rong fields. This transition was successfully implemented.

- Vietsovpetro also researched the application of associated gas for gas turbines and mechanical drives on gas compression platforms.

Since 2012, all power generation on Vietsovpetro's offshore installations in Block 09-1 has been fully fueled by associated gas.

To optimize the supply of offshore power resources at Block 09-1, Vietsovpetro conducted studies and developed a centralized power system, utilizing subsea power cables to distribute electricity across the entire field. This solution has brought significant savings for Vietsovpetro in the field operation and production in Block 09-1 on the Vietnamese continental shelf. From commissioning to December 31, 2019, the centralized power system had generated and supplied a total output of 772,454,100 kWh.

3.1.3. Using associated gas to replace FO/DO fuel for oil heating on processing platforms and FSOs

On the CPP-3, the boiler system providing heat for crude oil (T-1-A/B/C/D) used DO/FO oil. Vietsovpetro conducted research on using associated gas as a substitute for diesel oil (DO) for the boilers on CPP-3. Currently, the amount of associated gas used to maintain and stabilize the boiler system is about 18 - 25 thousand stm^3/day, replacing DO/FO fuel.

On FSOs, the high-capacity boiler systems for heating oil are used to heat crude oil before it is transferred to the processing tanks. In these tanks, water is separated to meet the specifications for commercial crude oil. Since 2014, on the VSP-02 FSO, Vietsovpetro conducted a study on recovering flash gas from breathing valves and proposed the installation of a gas compression station for utilizing this gas. The gas compression station gathers all flash gas released from the processing and cargo tanks, then compresses it to 5 atm, dries it, and supplies it for the boiler system as a fuel source, replacing DO/FO for oil heating on the FSO. The gas compression system on the VSP-02 FSO was commissioned in 2016, and by December 31, 2019, it had saved 7,358 tons of FO.

The aforementioned facilities have demonstrated high economic efficiency and made significant and sustainable contributions to the national economy, society, and environmental protection.

3.2. Effectiveness of applying research to production practice at Vietsovpetro

- From April 1995 to February 1997, Vietsovpetro supplied 579 million stm^3 of associated gas from the Bach Ho field to the Ba Ria thermal power plant.

- In 1997, Vietsovpetro supplied 2 million stm^3/day of gas to both the Ba Ria and Phu My 2.1 thermal power plants. The total additional volume of gas delivered onshore during this period was 233.2 million m^3.

- In 2008, the use of gas-saturated oil transport at the Bach Ho field to collect low-pressure gas, along with the installation of booster compressors marked a further milestone in associated gas recovery at oil and gas fields in Block 09-1.

- After 2010, when the DGCP was commissioned but could not gather all separated associated gas, Vietsovpetro's technological solutions achieved significant recovery of high-pressure associated gas from the Rong field. From October 2011 to December 2012, a total of 64.6 million stm^3 of associated gas was delivered to Bach Ho field then ashore. From November 2013 onward, an additional 1.0 million stm^3/day of gas was successfully gathered and utilized.

3.3. Economic efficiency of the project cluster

A cluster of projects on the research and application of technological solutions for the gathering, processing, and utilization of associated gas at Vietsovpetro's offshore fields and adjacent fields has brought significant economic benefits. The total economic efficiency of the project cluster is evaluated based on the effectiveness of the associated gas gathering and utilization solutions, as presented above:

- The effectiveness of the early gas gathering solution, delivering 1 million stm^3/day to shore without compressors and used as a substitute fuel for DO/FO at the Ba Ria thermal power plant (fast-track phase), is VND 1,471.69 billion (equivalent to USD 132.05 million) (Table 1).

- Effectiveness of the solution using an ejector to increase the gas transport capacity to shore to 2.0 million stm^3/day: It boosted the volume of gas transported ashore during the 1995 - 1997 period by 233.2 million m^3. The entire volume of gas was used as fuel for the Ba Ria and Phu My 2.1 thermal power plants, replacing 545.2 thousand tons of FO, with a cost saving of VND 654.60 billion, equivalent to USD 56.32 million.

- Effectiveness of associated gas gathering solutions from the Rong field, transporting it to Bach Ho CCP and then to shore (Rong field fast-track phase): Shown in Table 2.

- Comparison of efficiency of oil production by using gas-lift solution (in first phase) without gas compression platform versus the option of using gas compression platform: From March to June 1990, pilot tests were conducted using annulus gas of well 401/MSP-1 as gas-lift supply for wells 24, 27, 28, 36, 37, 38, and 46. After successful trials, from February 1993 to January 1997, the gas-lift oil production method without using compressors was expanded to wells 21, 24, 27, 28, 36, 37, 38, and 46 (using high-pressure gas separated from the products of wells 401 and 403/MSP-1). The total amount of oil extracted using the gas-lift method without compressors was 81,660 tons. The total amount of gas used was approximately 24,702,150 stm^3. The unit price for gas-lift compression in 1997 was USD 24.86 per thousand m^3. Therefore, the total cost savings achieved by using gas-lift for oil production without compressors were USD 0.61 million, equivalent to VND 6.91 billion (Table 3).

- Effectiveness of using associated gas as fuel for gas turbine engines to replace DO/FO for power generation on Vietsovpetro's offshore facilities: since the centralized power system was put into operation until December 31, 2019, the total electricity output of the system reached 772,454,100 kWh. Details of the electricity output from gas turbines are presented in Table 4.

The economic efficiency of the centralized power system is reflected in the cost savings gained by replacing individual diesel power stations. These savings are calculated based on the difference between the unit cost of generating electricity by individual diesel power stations and by centralized power supply, multiplied by the total power consumption of offshore facilities from the time the centralized power system was put into operation until December 31, 2019 (Table 5).

The total cost savings of Vietsovpetro for the period 2013 - 2019 is: 772,454,100 kWh × (USD 0.352 /kWh - USD 0.091 /kWh) = USD 201.86 million.

Table 1. *Cost savings calculation table from using gas to replace FO*

Year	Fuel gas volume		FO price	Cost if FO is used as fuel	Cost of gas purchase	Cost savings for power plants using gas instead of FO	
	Million m^3	FO equivalent, thousand tons	USD/ton	Billion VND	Billion VND	Billion VND	Conversion, million USD
1995	202.9	474.3	100	527.09	86.40	440.69	39.66
1996	287.8	672.8	133	988.37	206.10	782.27	70.99
1997	88.6	207.2	138	331.25	82.53	248.72	21.40
Total	579.3	1,354.3	-	1,846.72	375.03	**1,471.69**	**132.05**

Table 2. Cost savings from the early transportation of associated gas from the Rong field ashore

Year	Total volume of gas transported onshore		FO price	Cost if FO is used as fuel	Cost of gas purchase	Cost savings for power plants using gas instead of FO	
	Million m^3	FO Equivalent, thousand tons	USD/ton	Billion VND	Billion VND	Billion VND	Conversion, million USD
2011	5.4	12.7	675	175.63	37.84	137.79	6.70
2012	59.2	138.4	830	2,395.38	583.74	1,811.64	86.85
Total	64.6	151.0	-	2,571.01	621.58	**1,949.43**	**93.55**

Table 3. Economic efficiency of the oil production solution using gas lift without compressors

Well	Oil (tons)	Fluid (tons)	Gas lift (m^3)	Total cost savings from gas lift without using compressors (million USD)
21	4,474	9,585	1,437,750	0.036
24	18,489	45,796	6,869,400	0.171
27	19,845	19,882	2,982,300	0.074
28	9,557	17,284	2,592,600	0.064
36	1,633	2,429	364,350	0.009
37	1,194	7,130	1,069,500	0.027
38	11,060	35,425	5,313,750	0.132
46	15,408	27,150	4,072,500	0.101
Total	81,660	164,681	24,702,150	**0.614**

Table 4. Total electricity output from gas turbines as of December 31, 2019

Platform	Operating time		Average power generation capacity (kW)	Total electricity output from the start of operation to 31/12/2019 (kWh)
	Days	Hours		
PPD	2,266	54,384	5,500	294,479,800
CPP-3	2,043	49,032	7,950	380,133,400
GTG KPD	1,886	45,264	1,800	81,475,200
Typhoon	1,886	45,264	-	16,365,700
Total				**772,454,100**

- Economic efficiency of gathering gas on the VSP-02 FSO to replace DO/FO as fuel for crude oil heating in boilers.

Previously, FO as fuel was used for boilers on the FSO to heat crude oil, resulting in significant expenses for Vietsovpetro in the procurement and transportation of FO to the FSO. Meanwhile, flash gas released from the processing and cargo tanks on the FSOs was vented directly into the environment. Vietsovpetro conducted studies and invested in a gas recovery system on the VSP-02 FSO to collect flash gas, recover condensate for mixing with crude oil and utilize the recovered gas as boiler fuel. This solution has been then expanded to the VSP-01 FSO. By utilizing the gathered flash gas on the VSP-02 FSO during 2016 - 2019, Vietsovpetro saved approximately USD 4.86 million in FO costs (Table 6).

In addition, the economic efficiency of the solution to lower the dew point through subsea heat exchange, as well as the economic efficiency derived from the scientific content of Vietsovpetro's research and proposals for the construction projects of the CGCS, CCP, DGCP gas compression platforms and the two boosters at the Rong field, is considerable. However, due to insufficient data collection, it is not yet possible to quantitatively evaluate the economic efficiency of these solutions.

3.4. Social benefits and other sectoral benefits

In the 1990s, fuel for power generation was extremely scarce, while associated gas was being flared offshore (due to inadequate facilities). By using a fast-track design and construction solution, associated gas was gathered, processed, and transported to shore to supply the Ba Ria

Table 5. *Unit cost of diesel-generated electricity and gas turbine-generated electricity*

No.	Index	Unit	Value
A. Unit cost of producing 1 kWh using a diesel power station in 2013			
1	Total offshore electricity service cost in 2013 of the electrical engineering Enterprise (excluding diesel fuel)	USD	31,296,403
2	Total offshore electricity output in 2013	kWh	229,786,000
3	Diesel consumption per 1 kWh	liter/kWh	0.346
4	Average diesel price	USD/m²	495
5	Average transportation cost for 1 ton of goods from shore to offshore	USD/ton	152
6	Diesel fuel cost to produce 1 kWh	USD/kWh	0.216
7	Unit cost of producing 1 kWh using a diesel generator on offshore facilities	USD/kWh	0.352
B. Unit cost of producing 1 kWh of electricity using gas turbines and the centralized power supply system		USD/kWh	0.091

Table 6. *Economic efficiency of gas recovery for heating use on Vietsovpetro's FSOs as of December 31, 2019*

No.	Index	Unit	Year				Total
			2016	2017	2018	2019	
1	Volume of gas collected for use as boiler fuel on VSP-02 FSO	Ton	1,689.0	651.0	807.0	3,301.0	6,448.0
	Calorific value of gas	MJ/kg	47.59				
	Calorific value of FO oil	MJ/kg	41.7				
2	Equivalent FO volume (if gas had not been used)	Ton	1,927.38	742.88	920.90	3,766.89	7,358.1
3	Unit price calculation						
	FO oil price	USD/m³	396	429	495	594	
	FO oil density	Ton/m³	0,95				
	Converted FO oil price	USD/ton	416.84	451.58	521.05	625.26	
	Offshore cargo transportation cost	USD/ton	148.5	120.5	98	111.5	
	FO oil price at offshore facilities	USD/ton	565.3	572.1	619.1	736.8	
4	FO saved by using gas as boiler fuel	Million USD	1.09	0.42	0.57	2.78	**4.86**

thermal power plant. This brought a major transformation to Vietnam's industrial landscape and laid the groundwork for the establishment of the Phu My thermal power plants. Subsequently, it helped alleviate the energy crisis and reduce rotating power outages in the 1990s.

The application of technological solutions facilitated the gathering of associated gas from production fields in the Cuu Long basin, located on the continental shelf offshore southern Vietnam. Vietsovpetro's facilities have effectively become a hub for connecting and transporting gas from fields such as Rong, Rang Dong, Su Tu Den, Su Tu Vang, Su Tu Trang, Hai Su Den, Hai Su Trang, Te Giac Trang, Ca Ngu Vang, Thien Ung, and Dai Hung, contributing to enhance the efficiency of oil field development on the Vietnam continental shelf.

The gathering, processing and transporting of associated gas to shore by Vietsovpetro has delivered significant benefits to the Vietnamese economy. This initiative replaced traditional DO as a fuel source in thermal power plants and laid the groundwork for the development of new products such as urea, LPG, and raw materials for petrochemical plants, forming a solid foundation for the growth of the Vietnamese gas industry. Specifically, the production of urea fertilizer from domestically natural gas has contributed to ensuring national food security; LPG has contributed to urbanization, replacing traditional fuel sources in various industries. These developments have also created employment opportunities and increased household incomes. Gathering associated gas reduced offshore flaring, thereby lessening air pollution, maximizing of the

national resource recovery, and supporting sustainable socio-economic development.

4. Conclusion

The results of research, development, and implementation of associated gas gathering, processing, transportation, and utilization at fields in Block 09-1 and adjacent fields lead to the following conclusions:

Scientific and technological achievements: Successfully established and developed an integrated system of solutions for associated gas gathering, processing, transportation, and utilization. The developed technologies are grounded in solid scientific foundations, well-suited to actual field conditions, and have been implemented at Vietsovpetro and replicated nationwide.

Resource recovery efficiency: The application of solutions developed through this project cluster has increased the associated gas recovery and utilization rate from nearly 0% (previously almost entirely flared offshore) to over 90%, thereby enhancing the value of national oil and gas resources.

Hub connectivity role: Vietsovpetro's facility system has become a central hub for the gathering and transportation of gas, as well as the interconnection of offshore oil and gas fields in southern Vietnam, creating significant opportunities for investment and development in associated gas gathering from adjacent fields operated by Vietnam National Industrial - Energy Group and its partners.

Socio-economic contributions: Established a critical foundation for attracting domestic and international investments and for developing products that serve national economic growth, such as electricity, fertilizers, and chemicals. The successful implementation of these solutions has delivered substantial economic benefits to Vietsovpetro and Vietnam's petroleum industry.

Future prospects: The economic efficiency of this research cluster is expected to continue growing throughout the remaining life cycle of Vietsovpetro's field and will further expand as the facility system is connected to additional small and marginal fields in the future.

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